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INVESTIGATION OF FEASIBILITY OF A POSITIVE DISPLACEMENT INJECTOR FOR ATTITUDE CONTROL PROPULSION

Final Report
September 1962 - January 1963

Contract No. NAS 7-185

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Wright Aeronautical Division

Investigation of Feasibility of a Positive Displacement Injector for Attitude Control Propulsion

for

National Aeronautics and Space Administration

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I INTRODUCTION

An extensive number of devices have been considered for providing attitude control of space vehicles. Some of these have already been successfully applied while others are in the development or conceptual stage.

Any new concept for providing attitude control propulsion must possess the potential of demonstrating sufficient superiority to the existing techniques to warrant its development. That is, for contemplated requirements it must indicate sufficient improvement in one or more of the evaluating parameters used in selection of a particular system to justify its pursuit. In addition, it must be critically evaluated to determine that the concept can be implemented to result in a practical, reliable design.

Positive displacement injection is basically a variant of a conventional bi-propellant reaction control system which uses solenoid valves to control propellant flow. It differs in that mechanically linked fuel and oxidizer injectors coupled with an actuator replace the propellant solenoid valves.

The objective of this feasibility study has been to measure the potential of the use of this device for attitude control propulsion. It has thus attempted to establish that mission requirements exist or will exist for which it could be logically considered, that such a system would demonstrate superior performance to other possible schemes to warrant its selection for some of these missions, and that the operating principle can be practically mechanized.

II RESULTS AND CONCLUSIONS

The results of this study are summarized below:

a. Mechanical design of a reliable injector with adequate frequency capability and extended life appears entirely feasible.

b. A wide range in terms of total impulse requirements exists for which bi-propellant reaction control systems will represent the minimum weight attitude control system.

c. The requirement for systems in this range has been increasing and should continue to increase as programs of greater complexity develop.

d. The inert weight of components required by either a conventional bi-propellant system or one using the positive displacement injection principle will be essentially the same.

e. As the total impulse requirement increases the propellant weight becomes the predominant element of the system weight. The weight of inert components comprising the system therefore does not represent the potential saving in total system weight that can be achieved thru application of higher energy propellants or more efficient utilization of a particular propellant combination.

f. The positive displacement injector indicates considerable promise of being capable of operating in a manner which will result in materially improved propellant performance and thus reduced system weight.

   The technique utilized would be to inject the propellants into the combustion chamber within the propellant ignition delay time. Operation at high mean chamber pressure and consequent capability of using high nozzle expansion ratios within a reduced envelope is thus feasible. This results in an increase in theoretical propellant performance. Improvement in C* efficiency also appears possible. A discussion of the operating principle is contained in the body of this report.

In view of the indicated potential of the positive displacement injector for significantly improving propellant performance of a pulse engine, it is concluded that this device would be applicable to systems normally requiring a pulsing mode of operation for attitude control. A program for test evaluation of the injector to verify its capability of improving propellant utilization is thus suggested. A description of such a program is contained in Section VII.

III MISSION REQUIREMENTS

Ideally, applicability of the positive displacement injection principle potential would be accomplished by a comparative evaluation of systems using this device with other possible systems capable of satisfying mission requirements for definitive future applications. Demonstration of the superiority of the use of the injector for a number of these missions would clearly establish a need for such a device and justify its development.

Such an approach imposes the condition that control system requirements for advanced applications are defined. The results of a survey conducted as a part of this study program indicated that planning in such fine detail as to include specification of this subsystem is not common.

A questionnaire soliciting this type of information was prepared and submitted to various government agencies and industry prime contractors. In general, response to the questionnaire was restricted to data on applications either operational or in development.

Though the survey did not provide detailed information on specific future missions, it did serve two useful purposes. It provided a base for estimating order of magnitude requirements for future applications compatible with the more complex missions which will result as booster capability increases. It also indicated past and present trends in control system techniques. Information of this type even for developed vehicles has been meager and is only now becoming available in published compilations (Reference 1).

The results of this survey have been compiled and are included in Appendix A. It must be noted that the data presented in many cases probably does not represent the latest requirements. Some of the information was obtained from preliminary specifications. In other instances, changes have undoubtedly been made during the course of programs which would not be reflected in this compilation.

The survey results have been classified into two basic groups. The first of these include that class of missions for which the attitude control system's normal mode of operation will consist of single impulse corrections. That is, it will correct for impulsive disturbances or prolonged disturbances of low magnitude for which continuous operation of the control system would not be practical and in limit cycle. Earth orbiting vehicles of the non-maneuvering type are the prime representative of this class.

The second group of missions include those for which a high duty cycle possibly including long periods of steady state operation is to be expected. Under such conditions, a capability for pulse width modulation appears desirable. In general, steady state operation will result in a performance improvement compared to a pulsing engine producing the same total impulse over an equal time increment. The positive displacement engine limited to impulse bit operation would usually not be competitive with a conventional system capable of pulse width modulation for this type of mission. Representative of this latter class are attitude control engines for use during thrusting phases of booster operation, missions requiring mid-course or other maneuvering as a significant percent of the control systems total impulse capacity or control during high magnitude disturbances of a prolonged duration such as for earth re-entry.

The positive displacement injector under consideration is thus primarily suited to missions requiring a pulsing mode of operation. For this application, the feasibility of the device was investigated using estimated requirements for missions of this nature as will be described in Section IV.

Based on the compilation of control system requirements and types of systems applied to date, the following general conclusions can be drawn:

a. Total impulse, thrust level and impulse bit magnitudes have in the past been low for orbiting type vehicles.

b. Cold gas, monopropellant and reaction wheel systems have been applied to vehicles using an active type of control system to a much greater extent than the high energy bi-propellant system. However, the bi-propellant system is now finding greater application as total impulse requirements increase.

Payloads for both orbiting type missions and those requiring propulsion phases have in the past been restricted by booster capability. Development of the Saturn and Nova class of boosters will permit much more complex missions of extended duration and with much heavier payloads. These more complex missions should produce a greater requirement in terms of control system total impulse capability.

The Gemini and Apollo programs illustrate the trend toward a higher total impulse capability which has resulted in the selection of a bi-propellant system. The propellant weight would be excessively high if monopropellants or cold gas were to be used for these applications. A reaction wheel or other inertial system is not feasible for this type of requirement as will be discussed under the consideration of various systems.

In that definitive requirements were not available, it was necessary to adopt a revised approach to establish a basis for evaluating the applicability of the positive displacement injector. Assumptions in terms of the control system's total impulse, thrust level and impulse bit requirements were necessary. This is disucssed in Section IV. It was still desirable to attempt to predict advanced mission requirements to establish that the assumed values for design parameters were of the right order of magnitude and also to establish the basis for the preliminary design of a particular system using the positive displacement injection principle. The latter is a part of this study program and is described in Section VI of this report.

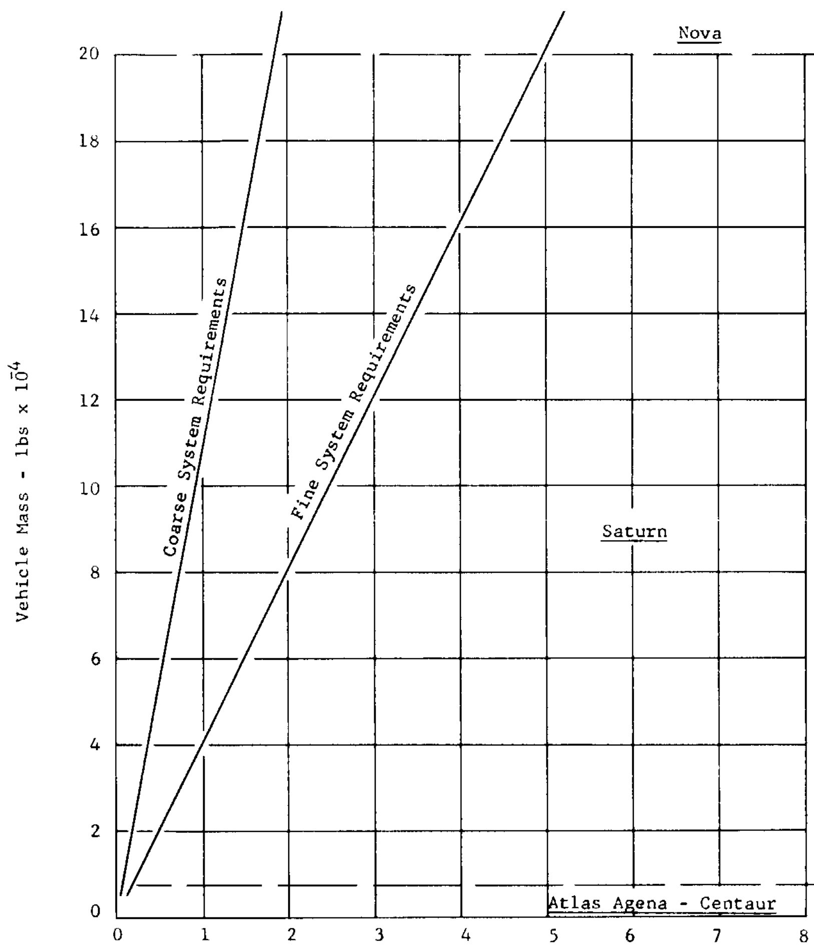
The data for the class of missions compatible with a pulse system was thus considered. A relationship in terms of the payload weight and time in orbit was evident and appeared to present a simplified method of predicting order of magnitude control system requirements. Using payload weight as a parameter is also desirable in that booster capability can be conveniently represented.

Data points were thus plotted and a relationship in terms of total impulse versus payload weight established. This relationship is depicted on Figure 1. It must be realized that the presentation is only order of magnitude. Data points reflected a wide scatter as would be expected in that a particular mission requirement is dependent upon numerous factors other than payload weight. These include pointing accuracy, vehicle configuration and moments of inertia, slewing requirements and the anticipated disturbances to which the vehicle is likely to be subjected.

A further estimate in terms of thrust level and impulse bit again related to payload weight was made and is presented on Figure 1. These values can also only be considered very approximate with considerable variation on either side to be expected dependent upon particular mission requirements.

Referring to Figure 1, it is to be anticipated that control system total impulse requirements will increase as the Saturn and Nova type boosters become available. The systems comparison analysis for this study based upon this projection should thus be extended to total impulse requirements or its equivalent well in excess of those values which are representative of present day applications.

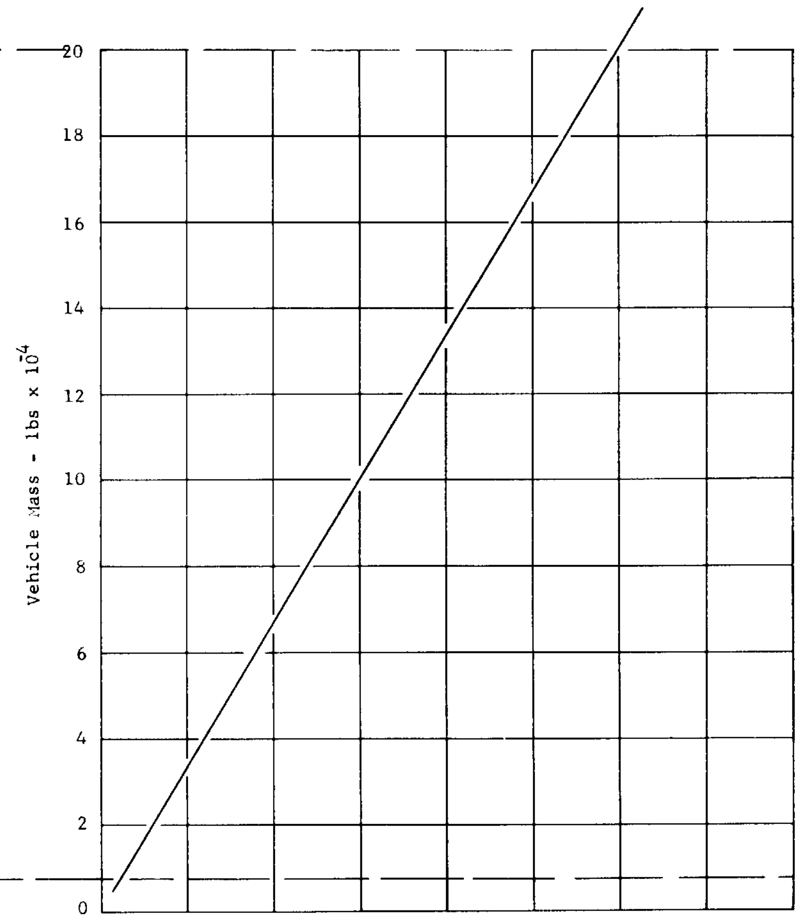
ESTIMATED TOTAL IMPULSE
REQUIREMENTS
ORBITING VEHICLES



Total Impulse (Lb-Secs x 10^5) Required per Year

Station Keeping and Attitude Control
Orbiting Vehicles

ESTIMATED THRUST LEVEL AND
IMPULSE BIT REQUIREMENTS
ORBITING VEHICLES



Estimated Coarse System Requirements

0	25	50	75	100	125	150	Thrust Level (lbs)
0	.25	.50	.75	1.00	1.25	1.50	Impulse Bit (lb-secs)

Estimated Fine System Requirements

0	.25	.50	.75	1.0	1.25	1.50	Thrust Level (lbs)
0	.0025	.0050	.0075	.0100	.0125	.0150	Impulse Bit (lb-secs)

Figure 1

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IV COMPARATIVE EVALUATION OF SYSTEMS FOR ATTITUDE CONTROL PROPULSION

A. Positive Displacement Injection Concept

The first step required in evaluating the potential of the positive displacement injector was a consideration of the mechanical design of the device and its operating characteristics.

(1) General Description:

The positive displacement injector (PDI) is a propellant metering pump similar to a fuel injection pump for an internal combustion engine. It is designed to inject accurately measured quantities of fuel and oxidizer into a thrust chamber at a pressure level required to produce a desired injection velocity. The propellant is pressurized within the injector therefore permitting the use of a low pressure feed system.

(2) Mechanical Design:

A schematic representation of three PDI designs is shown in Figures 2 through 4. Figure 2 shows a gas actuated piston type design. The main components of this system are the piston, bellows, check valve, and poppet valve. Fuel is fed into the injector at supply pressure filling all cavities. When the piston is actuated, the check valve is in the closed position and the fuel is pressurized to the desired level. The high pressure opens the poppet valve and the fuel is injected into the thrust chamber at the desired injection velocity. The metallic bellows provides a positive dynamic seal between the piston shaft and its housing. The bellows also acts as a spring returning the piston to its original position after the injection stroke. Close fits between the piston and housing and the poppet valve and housing minimize fuel leakage during the injection stroke. Any fuel leakage past these components is returned to the supply system.

Figure 3 shows a gas actuated bellows type PDI. In this design a bellows instead of a piston is used to pressurize and displace the required volume of fuel. When the bellows is being extended, the increased pressure opens the poppet valve injecting a predetermined volume of fuel into the combustion chamber. The check valve seals the feed system from the high pressure. The poppet valve is dynamically sealed by a bellows. The close fits used for sealing the piston type PDI are eliminated in this design. The bellows spring force returns both the poppet valve and pressurizing bellows to their original positions after the injection stroke.

The third design (Figure 4) is a piston type PDI without a check valve. The piston takes over the function of a check valve by opening and closing an inlet port. In the open position, supply pressure fuel is fed through this port priming the poppet valve. On the down stroke the piston closes this inlet port sealing the high pressure from the feed inlet. The piston is position sensitive relative to the inlet port, therefore, a piston position adjustment is included in the design. The operation of this system is identical to that of the piston with check valve design (Figure 2) previously discussed.

Figure 5 shows the two actuating systems. One system used a gas driven piston to actuate the fuel and oxidizer pistons on the injection stroke. The return stroke is accomplished by the piston bellows spring force. Gas flow is controlled by a solenoid pilot valve. The gas piston is attached to a single mechanical yoke which contacts both fuel and oxidizer piston rods. Synchronous actuation of the fuel and oxidizer pistons is obtained with this system.

The other actuating system is the reverse of the gas actuating system. In this design, a spring is used to drive the gas piston on the injection stroke. Gas pressure is used to drive the gas piston for the return stroke. In the design shown continual gas input would be required to keep the mechanism cocked resulting in a considerable gas weight penalty. This feature could be eliminated by using a bellows as a positive seal, however, this complicates the design, therefore lowering reliability.

The designs described above are all feasible, mechanically simple methods of accomplishing the PDI principal. The piston type design is similar to that used successfully in Diesel injectors. It's undesirable feature is the close fit required between the fuel and oxidizer pistons and their housings.

The bellows displacement PDI eliminates the requirement of a close fit between the piston and housing. This design also reduces the envelope of the injector by the elimination of the piston length.

Elimination of the check valve from the piston type PDI increases the piston stroke and therefore increases the required amount of pressurizing gas. This system can be used only with the piston type PDI.

The common feature of these designs is the separation of components facilitating optimum packaging. Separating the check valve from the injector piston makes the valve independent of the piston size.

Variations in the impulse bit obtainable with these designs was considered. It was concluded that the minimum impulse bit engine is basically controlled by the injection orifice size rather than other considerations such as minimum piston diameter or stroke. To achieve a propellant injection velocity of the order of 100 feet per second and to keep the injection orifice to a practical size, an impulse bit of approximately 0.10 lb-secs is considered a minimum obtainable. There is no particular restriction on the maximum impulse bit. Designs can be scaled to produce virtually any impulse bit above the minimum.

A survey showed that materials are available which are compatible with the propellants investigated in this report. The device is thus applicable to a wide range of propellant combinations.

POSITIVE DISPLACEMENT INJECTOR

Piston Displacement

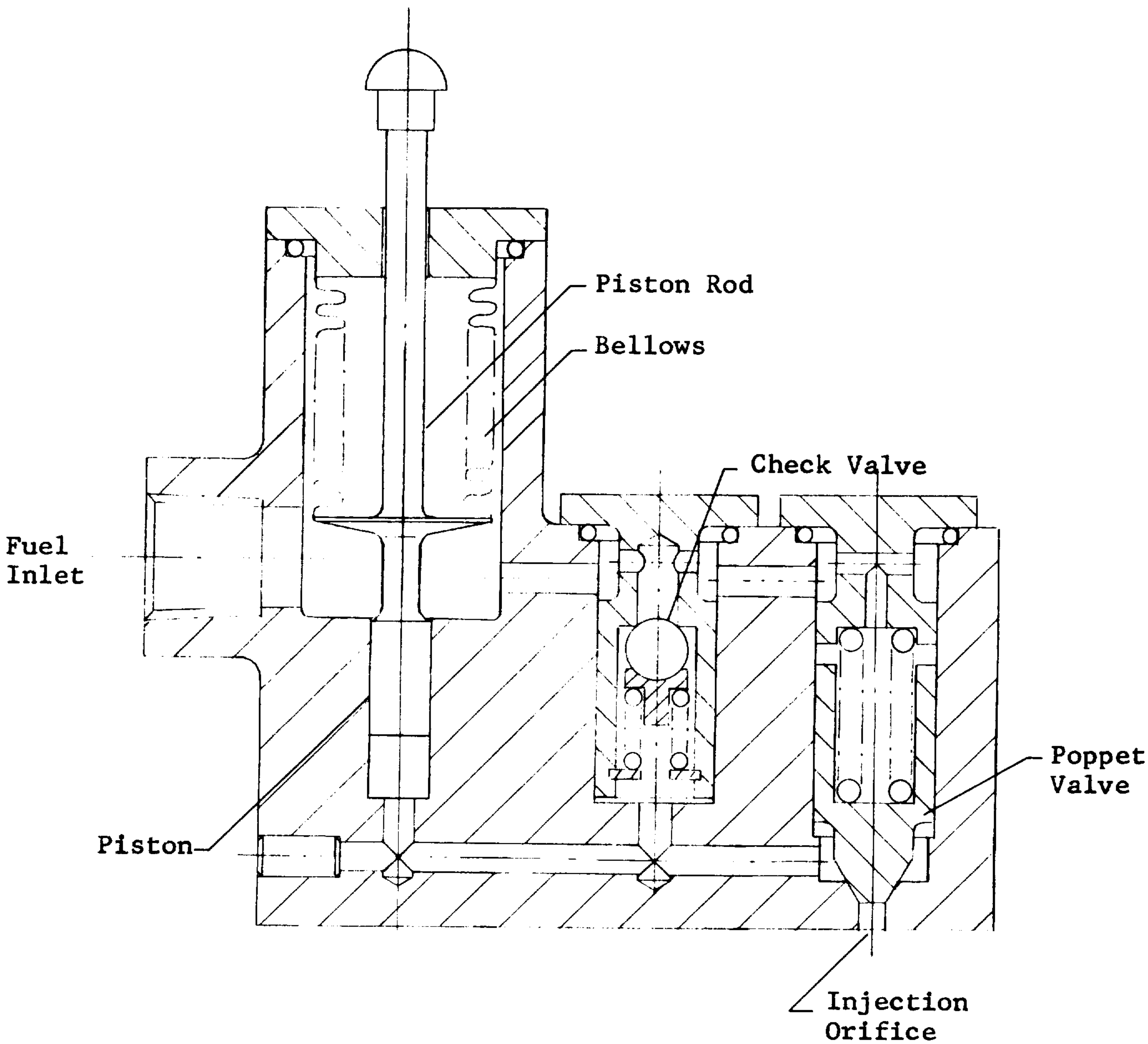

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Figure 2

POSITIVE DISPLACEMENT INJECTOR

Bellows Displacement

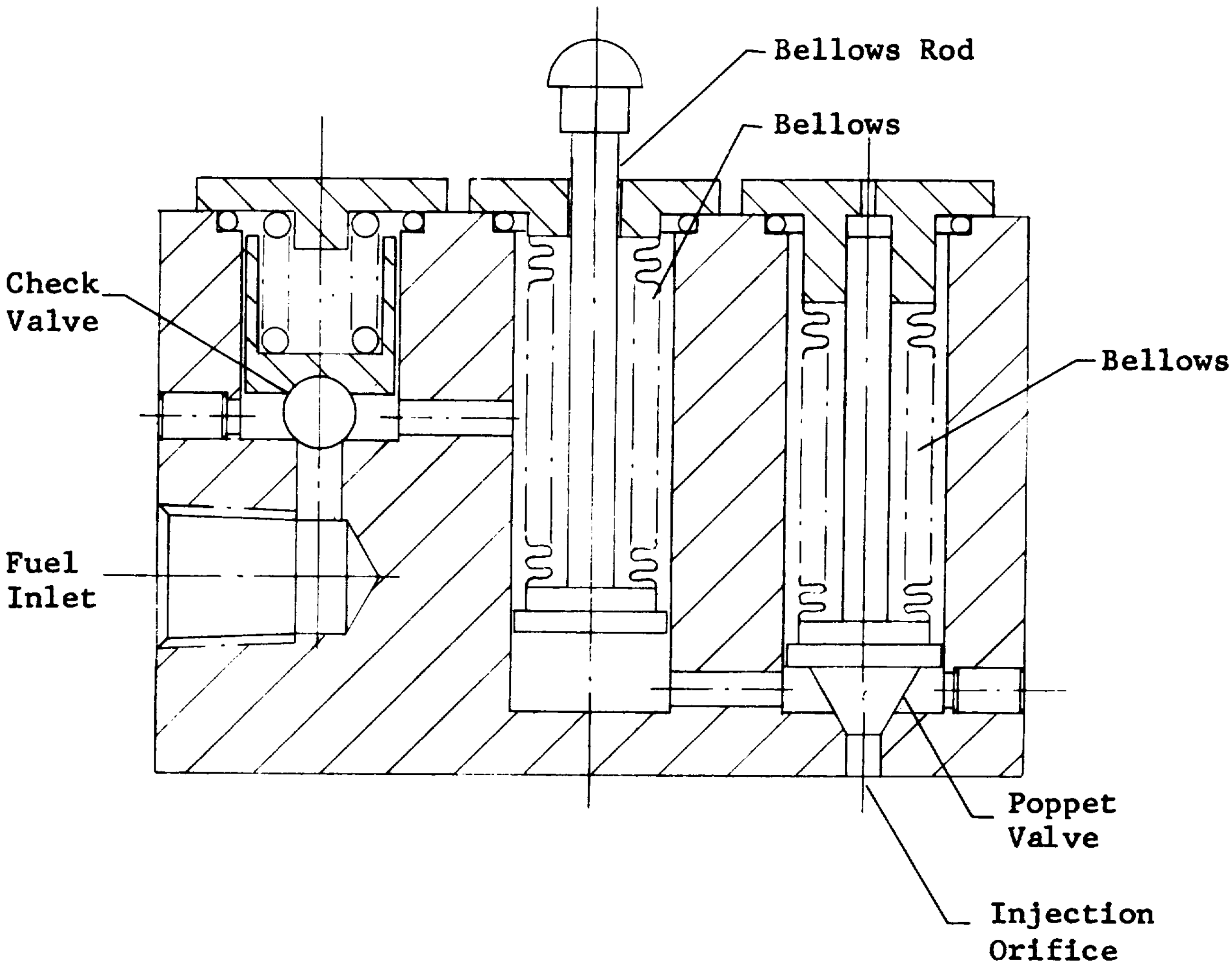

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Figure 3

POSITIVE DISPLACEMENT INJECTOR

Piston Displacement
(No Check Valve)

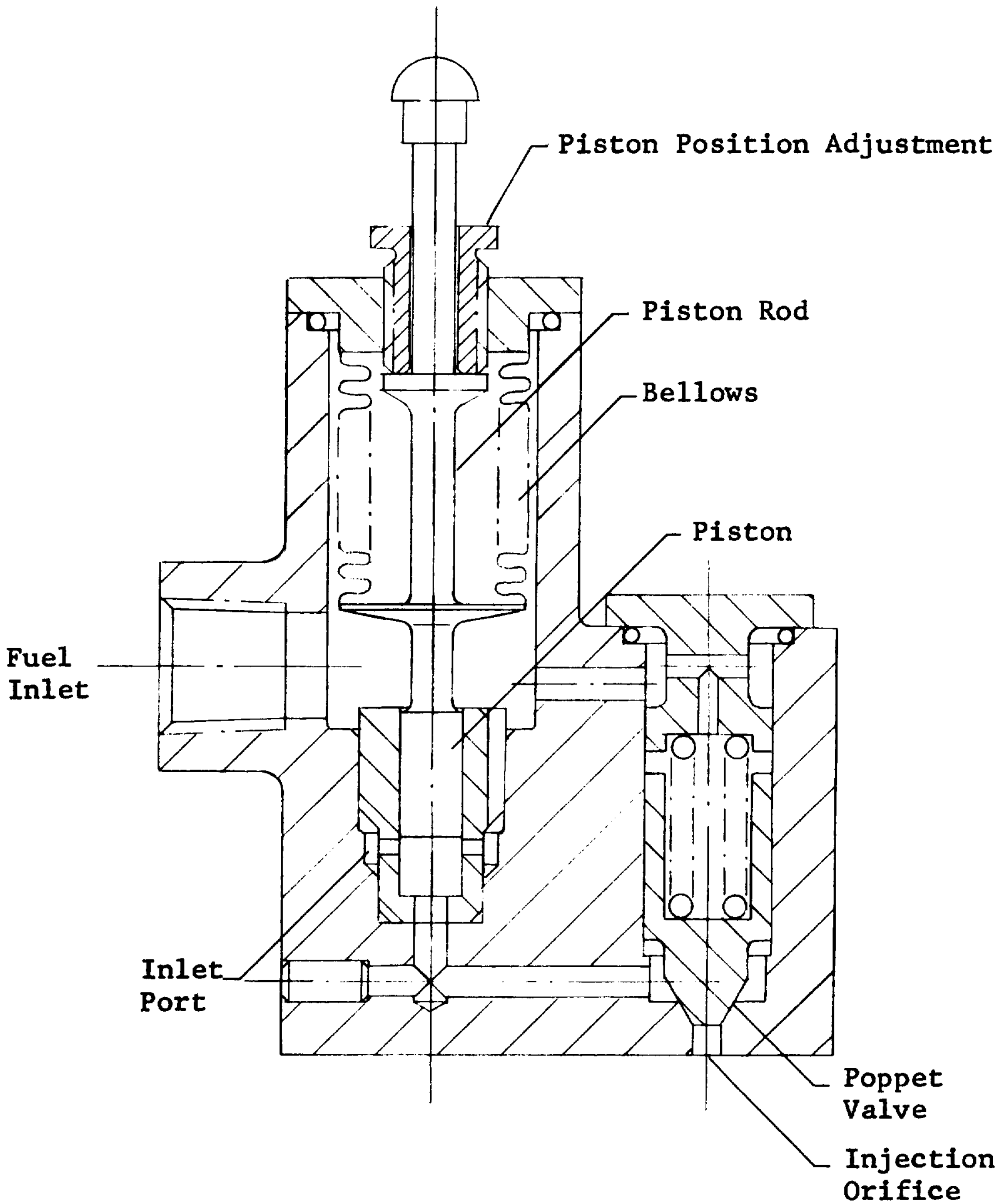

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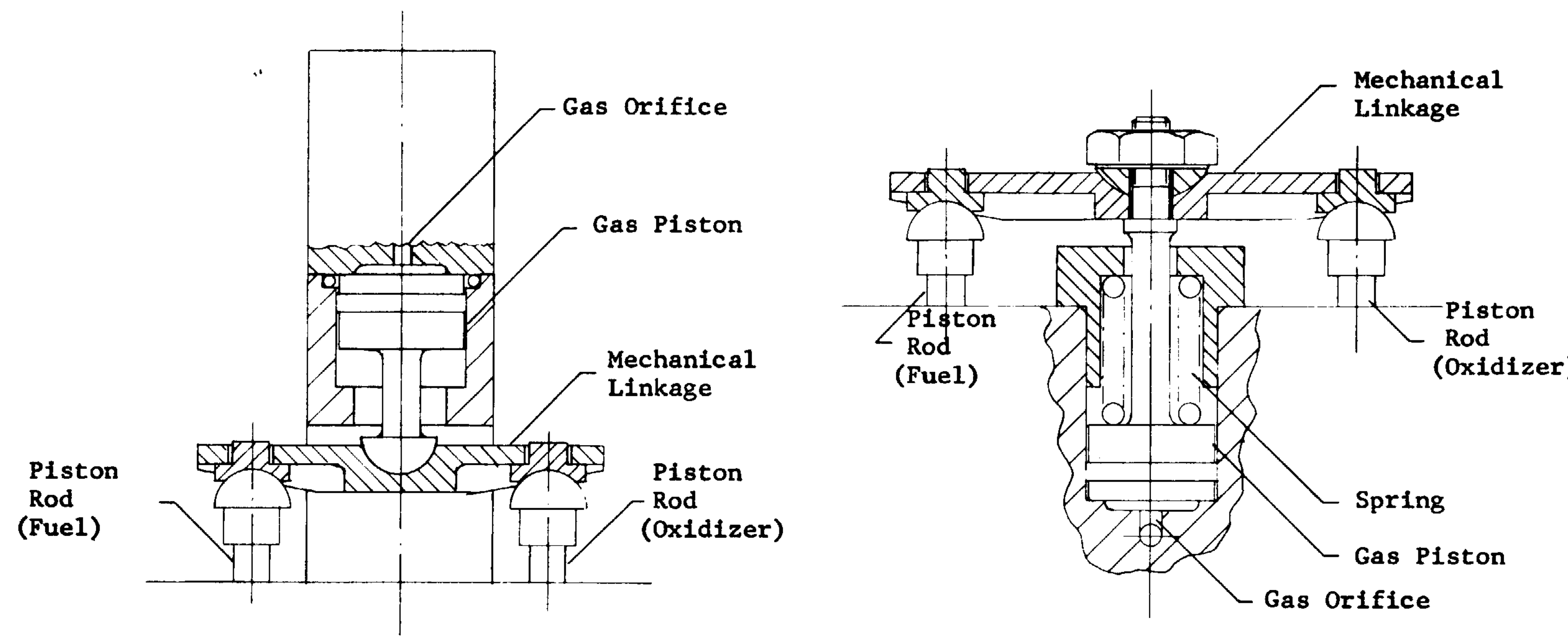
Figure 4

PDI GAS ACTUATING SYSTEMS



Gas Actuated
Spring Returned

Spring Actuated
Gas Returned

Figure 5

(3) Dynamic Analysis:

Four designs of the Positive Displacement Injector; pressure actuated piston type (Figure 2), pressure actuated bellows type (Figure 3), piston type PDI without a check valve or port type (Figure 4) and spring actuated - gas returned piston type (Figure 5) were analyzed. They were compared on the basis of the ability to inject accurate quantities of propellant, pilot valve weight and power requirements, the amount of nitrogen required per pulse, injector weight and pulse repetition rate.

The comparison was made for an injector designed for a 0.1 lb. sec. impulse bit. The propellants were N_2O_4 and a 50-50 blend of UDMH, N_2H_4 having a theoretical specific impulse of 316 seconds at an oxidizer-fuel ratio of 1.4. For pulse operation, this specific impulse was degraded to 80% of its steady-state value. Other parameters were: 100 feet per second propellant injection velocity; 400 psi chamber pressure; 80 psi propellant feed pressure; and 300 psi nitrogen supply pressure.

a. Ability to Inject Accurate Quantities of Propellant

The ability to inject the desired quantity of propellant per stroke depends on the accuracy of the bellows or piston and cylinder diameters and of the stroke. The critical diameters of the three piston type of injectors can be machined to tolerances of $\pm$ .0002 inches. Bellows cannot be obtained with quite this degree of precision; however, the use of matched pairs could overcome this difficulty. There would not be any difference in the accuracy of the stroke for any of the four types.

b. Pilot Valve Weight and Power

The weight and power requirement of the solenoid pilot valve depends on its orifice diameter and response time. Since the same pilot valve response would be desired for each type of injector the orifice diameter would be the controlling factor. The orifice diameters for an injector actuation time of 10 milliseconds, which would be required for a 10 pound thrust engine with a 0.1 lb. sec. impulse bit, are shown in Table 1. Since they are so similar there would not be any significant pilot valve weight or power differences between any of the four types of injectors.

These diameters were obtained from curves similar to Figure 6 which shows the injector response vs. pilot valve orifice diameter for the pressure actuated type of injector. These curves, and any others which show the response of the injector, were plotted using points obtained from the solution of the equations in Appendix "B". The equations for "fill", "actuate" and "return" have been programmed for solution by the IBM 704 digital computer. The "fill" time is the time required to fill the volume above the piston to a pressure high enough to overcome the resisting force and start the piston moving. "Actuate" is the time required for the piston to move thru its stroke and inject the propellant. "Vent" is the release of the gas pressure in the cylinder to the point where the piston starts to move. "Return" is the return stroke. "Total" is the sum of the fill, actuate, vent and return time. The total cycle time of the injector will be this "total" time plus the cycle time of the solenoid pilot valve. Since the response of a solenoid valve can be changed by using pulse shaping or changing the solenoid, the "P.D.I. cycle time" in this discussion will refer to the pneumatic portion of the injector only: i.e.: the above "total" time.

c. Injector Weight, Volume of Nitrogen Required Per Stroke and Pulse Repetition Rate

Injector weight and size will be affected by the actuator piston area. If the piston area for one is much larger than another, it will require a larger and heavier injector. The amount of nitrogen required per stroke depends on the length of the stroke, the area and the volume between the top of the piston and the pilot valve orifice. This volume was taken as 0.1 x (actuator piston area) in order to simplify the calculations. The stroke was 0.14 inches which was obtained by using a stroke/oxidizer piston diameter ratio of 0.7. This ratio was found to produce the smallest error in volume due to stroke and diameter tolerances (see Appendix C). The actuator piston area was obtained by varying the spring rate, preload and area to determine their effect on response, and then selecting the combination which resulted in minimum P.D.I. cycle time and piston area.

Figure 7 shows that the spring rate has comparatively little effect on the total time. Since design considerations such as the desired spring preload, and available bellows, spring sizes and space would most likely be important enough to govern the actual spring rate, a representative value of 50 pounds per inch was used for this study. The pilot valve orifice diameter used was 0.0252 inches (.0005 $in.^2$ area). Curves of actuator piston vs. response, such as Figure 8 for the pressure actuated type, were plotted for various values of preload and were used to obtain Figures 9, 10 and 11. They show preload vs. minimum cycle time, actuator piston area for minimum cycle time and actuation time at minimum cycle time. The spring preload used was the one which resulted in the minimum cycle time, as shown in Figure 9. The actuator piston area for this preload was obtained from Figure 10, and the actuation time from Figure 11. The results of this study, Table 1, show that there is not enough of a difference in the actuator piston areas to effect the injector size and weight. The pressure actuated and bellows types use the least amount of nitrogen per pulse. They and the spring actuated type have the same pulse repetition rate capability and one that is greater than that of the port type of injector design.

COMPARISON OF VARIOUS INJECTOR DESIGNS

Type of Injector Design	Pilot Valve Orifice Dia. for 0.01 Sec. Actuation Time	Preload for Minimum Cycle Time	Minimum Cycle Time	Actuation Time at the Minimum Cycle Time	Actuator Piston Area for Minimum Cycle Time	Volume of Nitrogen Per Stroke
	Inches	Pounds	Seconds	Seconds	$In.^2$	$In.^3$
Pressure Actuation	.0203	0	.0223	.0065	.116	.0278
Spring Actuation	.0204	33	.0223	.00655	.121	.029
Bellows	.0203	0	.0223	.0065	.116	.0278
Port	.0236	5	.0299	.00875	.139	.0375

Table 1

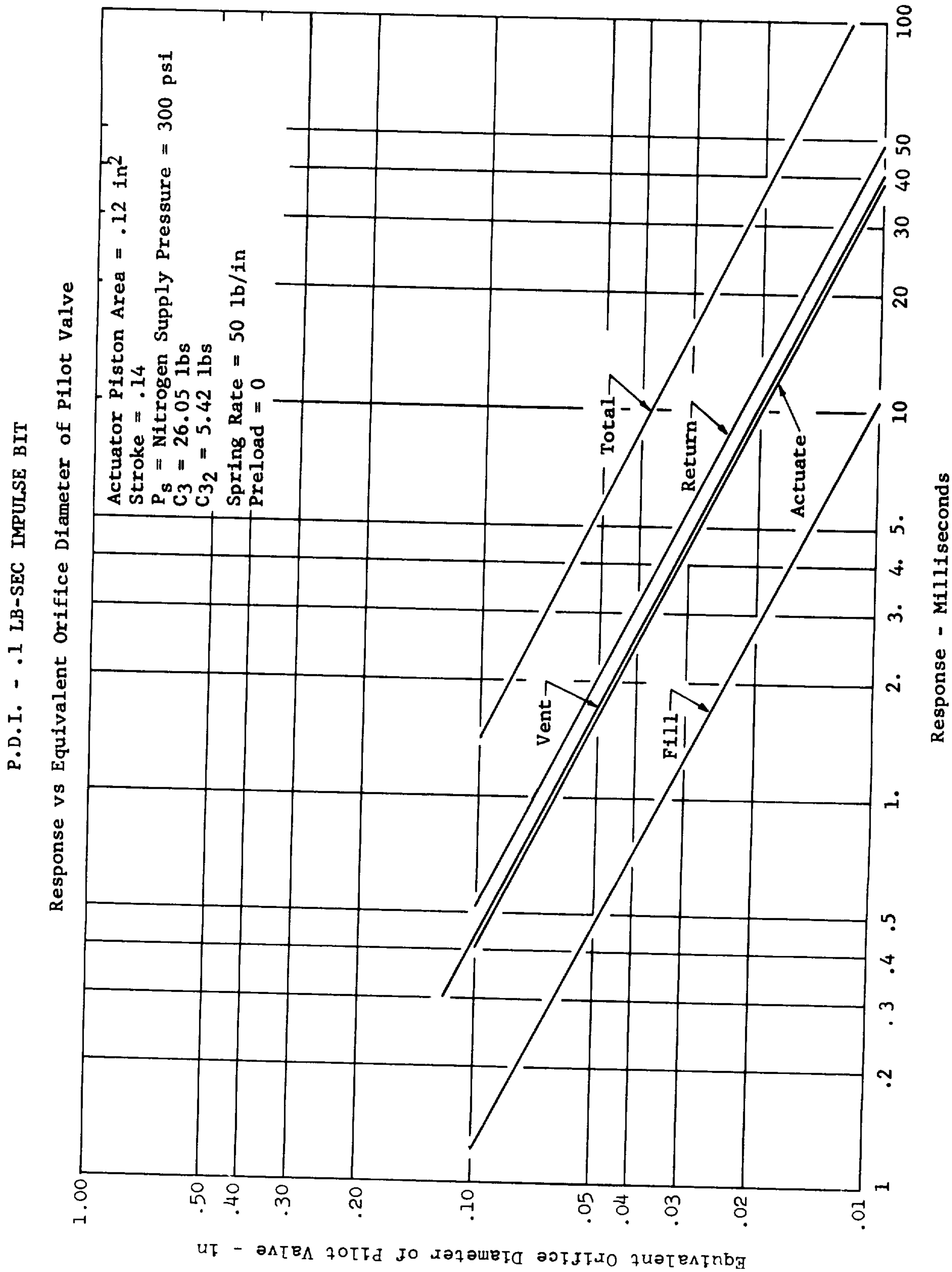


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Figure 6

RESPONSE VS SPRING RATE

P.D.I., .1 Lb-Sec Impulse Bit

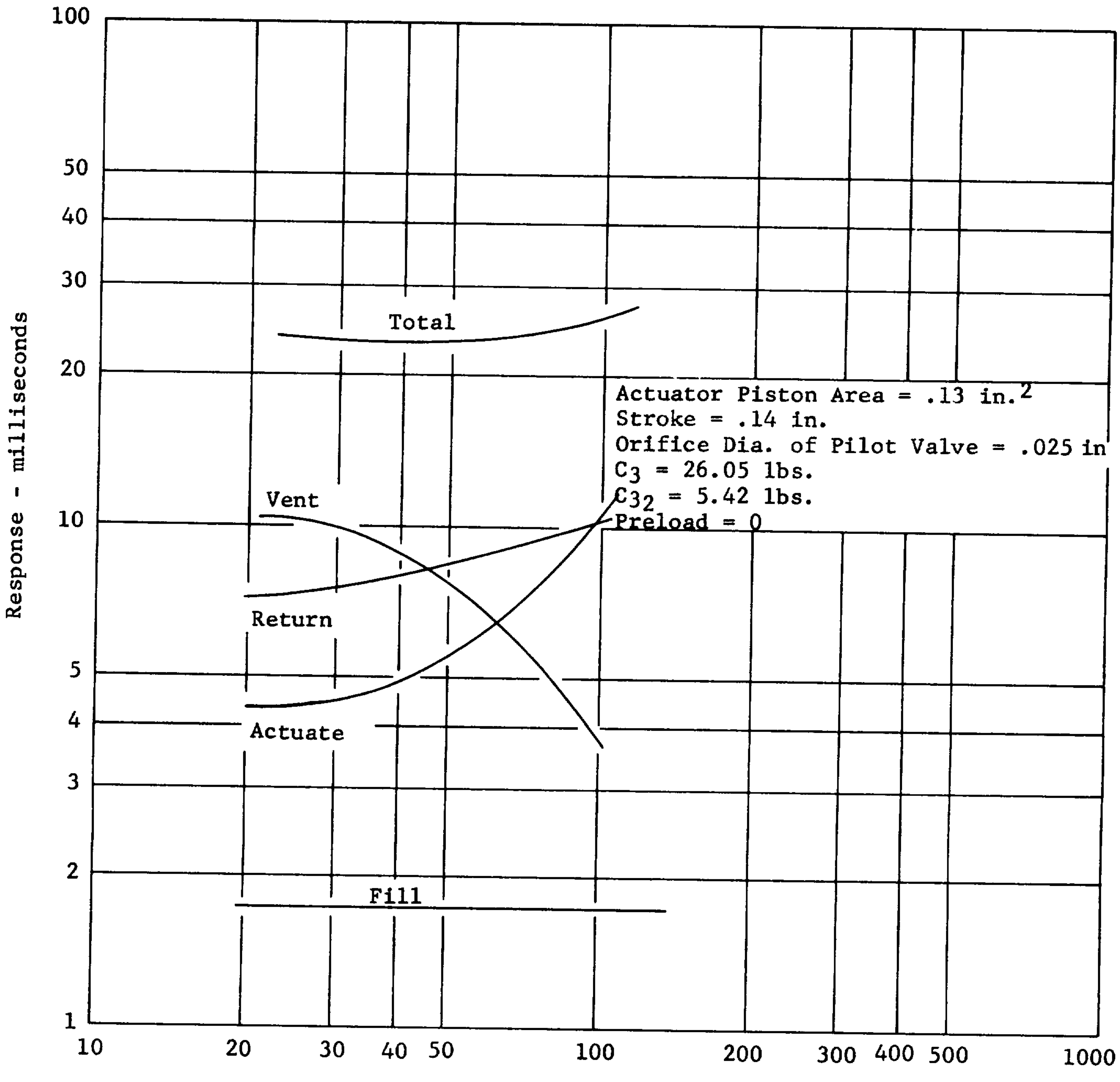

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Figure 7

P.D.I. - .1 LB-SEC IMPULSE BIT

Response Vs Actuator Piston Area

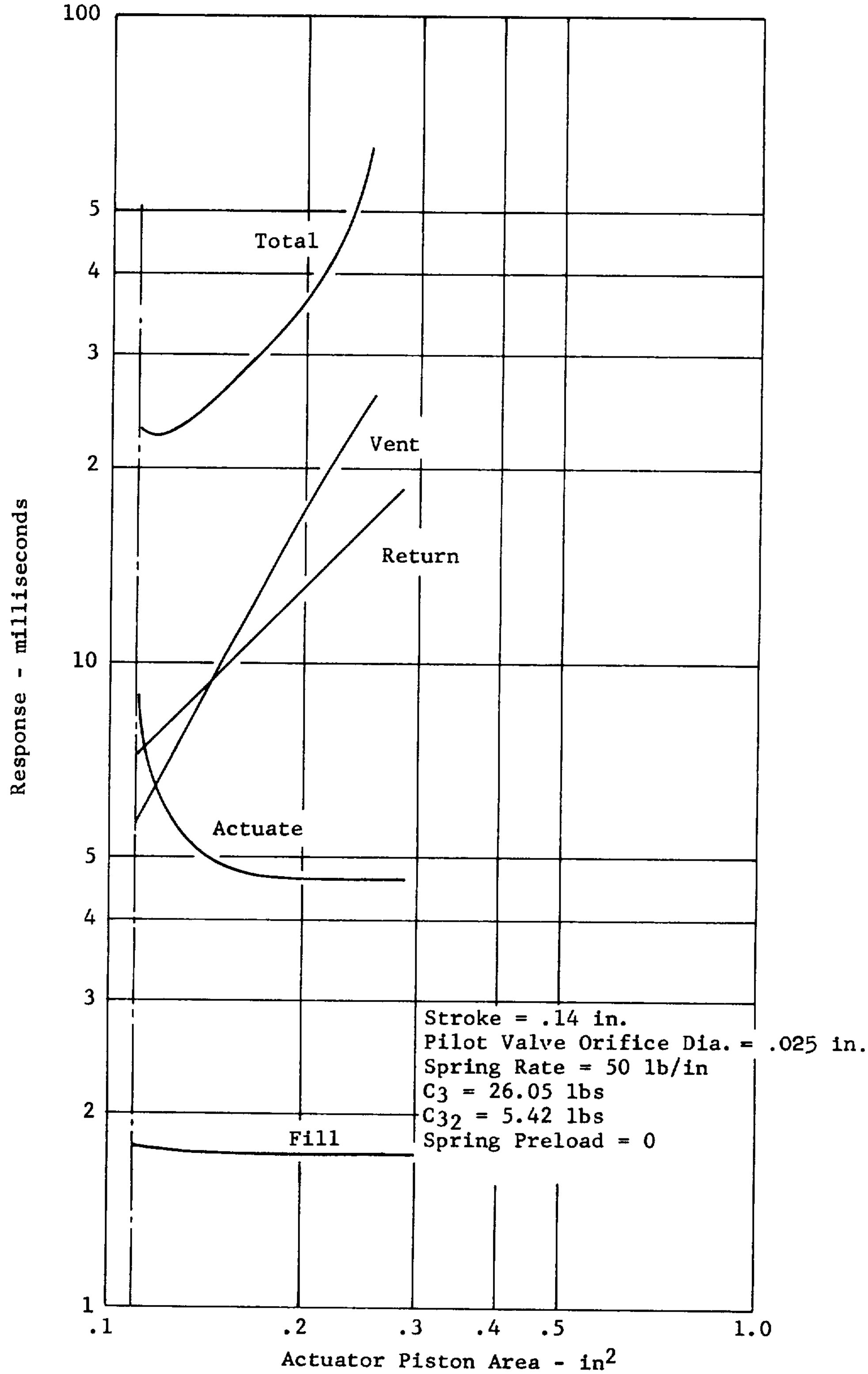

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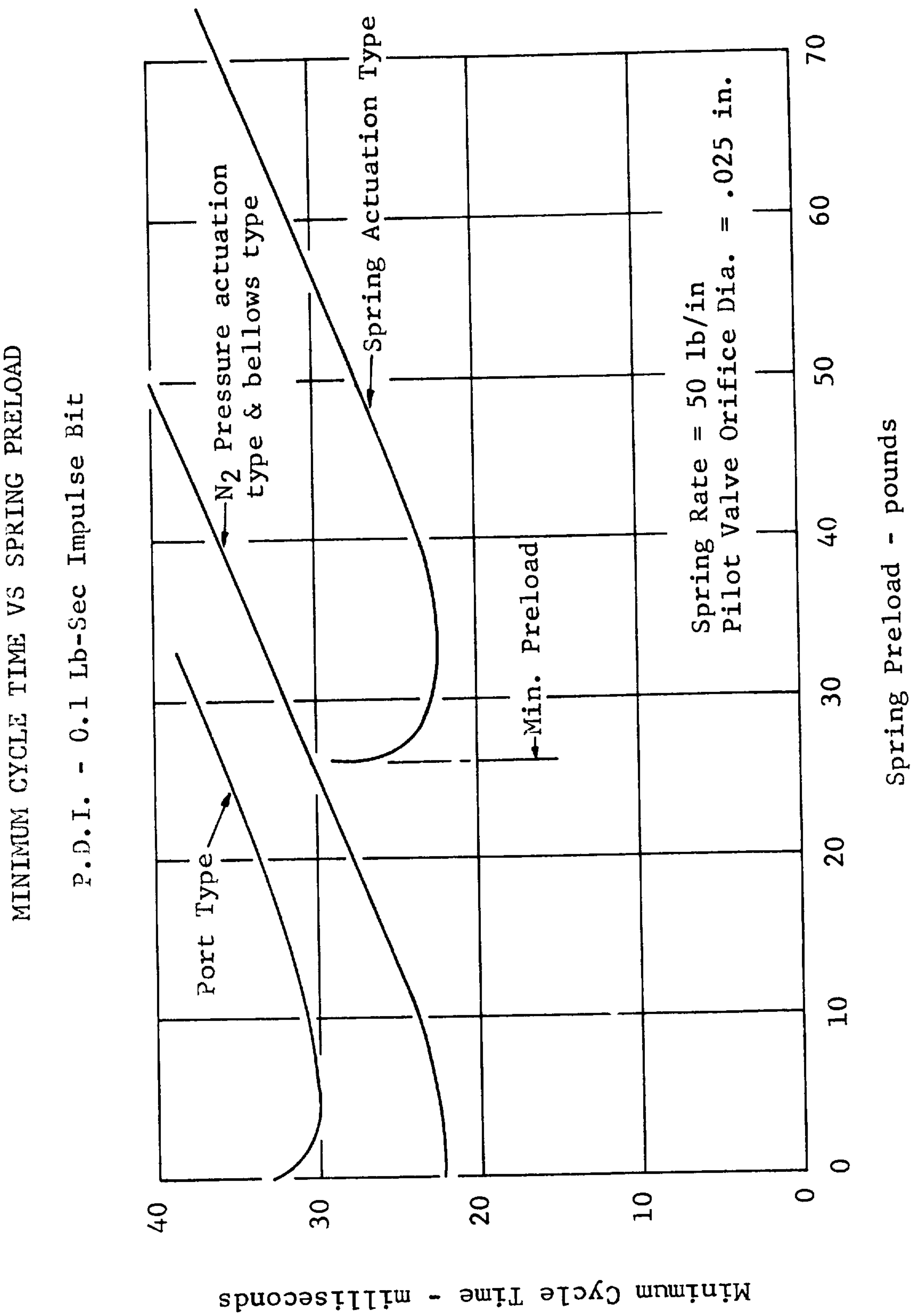
Figure 8



MINIMUM CYCLE TIME VS SPRING PRELOAD
P.D.I. - 0.1 Lb-Sec Impulse Bit
Port Type
N_2 Pressure actuation type & bellows type
Spring Actuation Type
Min. Preload
Spring Rate = 50 lb/in
Pilot Valve Orifice Dia. = .025 in.
Spring Preload - pounds
0
10
20
30
40
50
60
70
Minimum Cycle Time - milliseconds
0
10
20
30
40

Figure 9

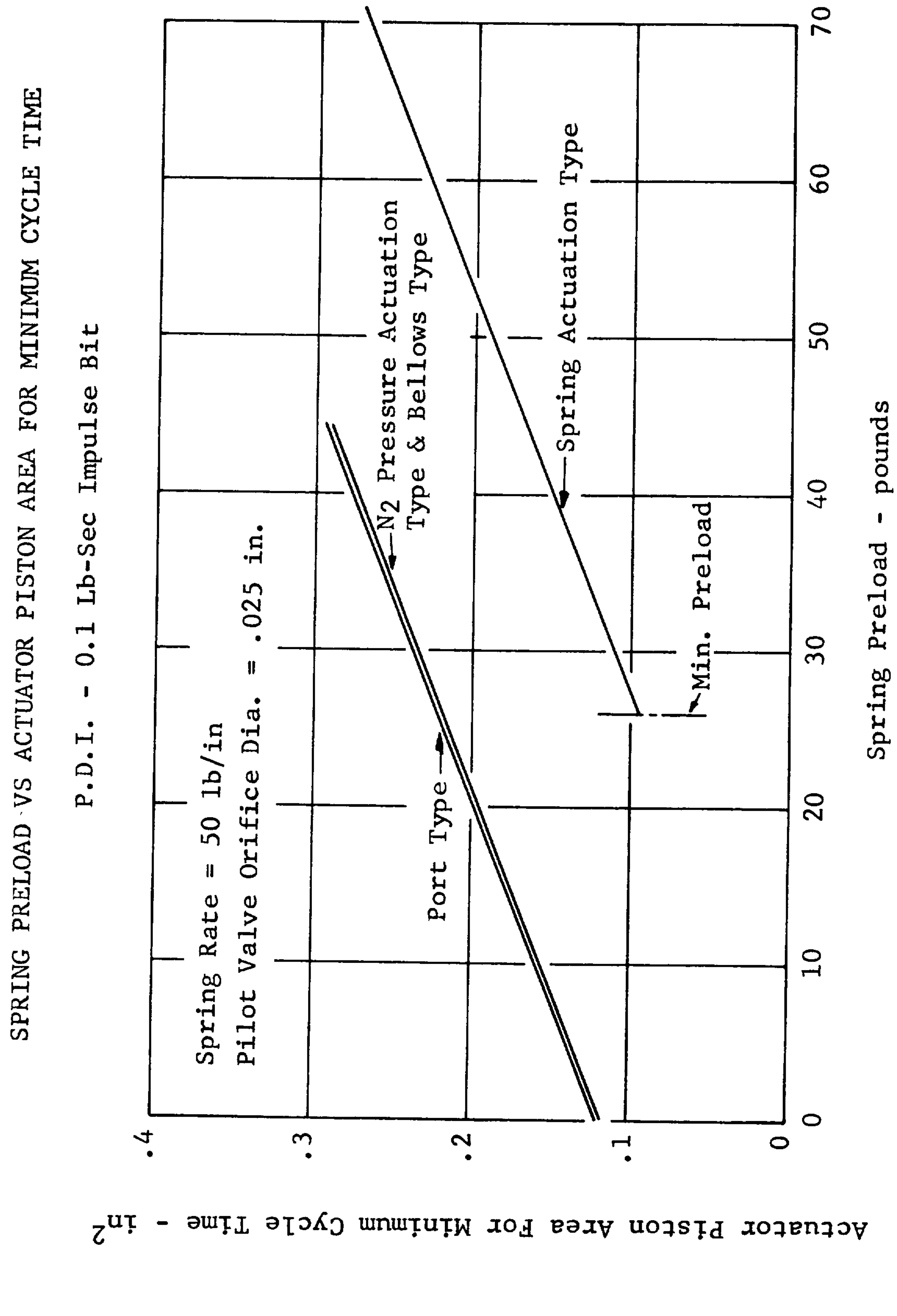


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Figure 10

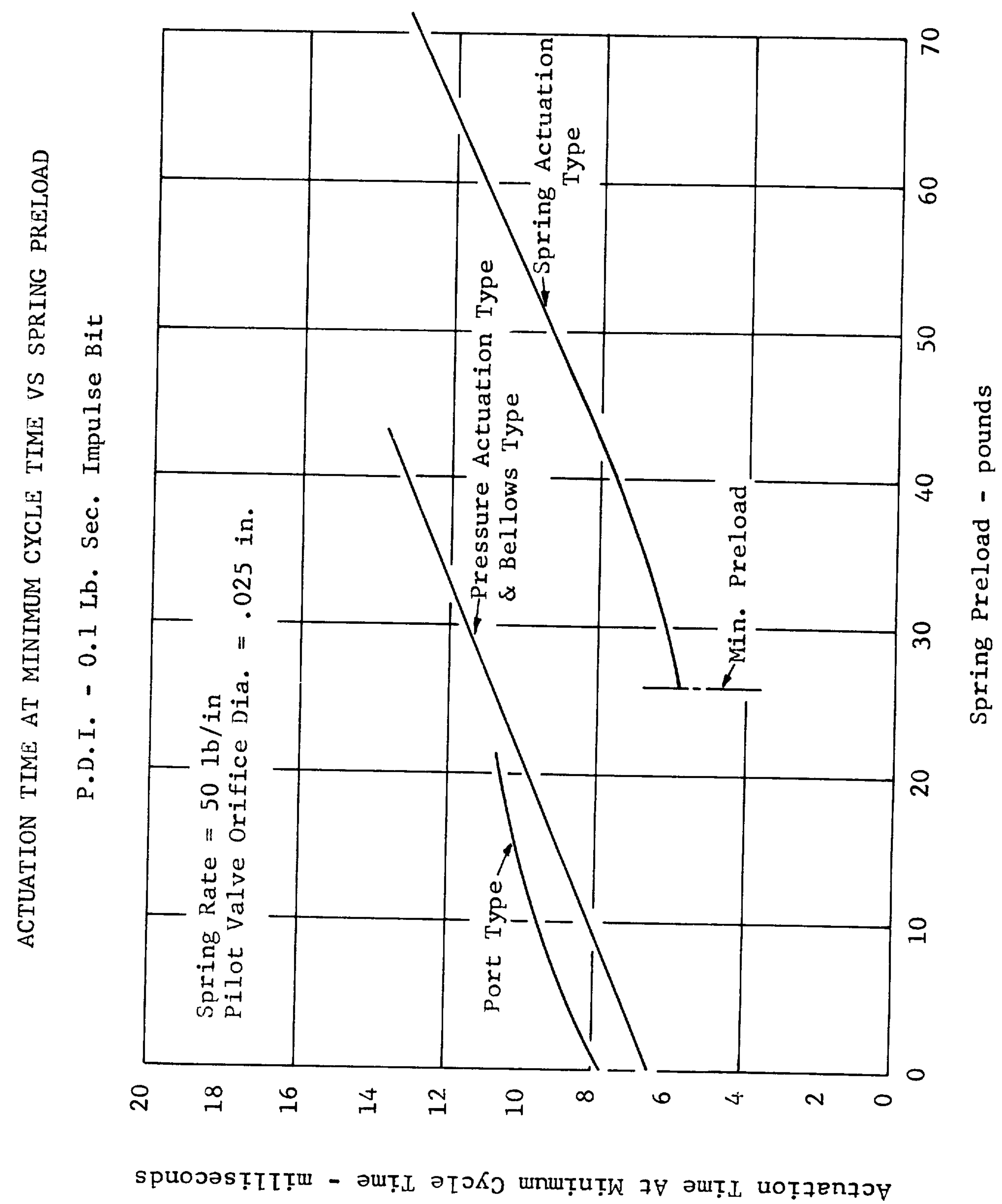

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Figure 11

B. Evaluation of Various Systems

The design analysis provided a means of estimating injector component weight and actuating gas requirements requisite to a PDI control system weight estimate. It was now possible to evaluate the positive displacement injector concept by comparing it to various alternative systems capable of producing a specified control function. The procedure used and the results of this analysis are discussed below:

(1) Selection of Alternative Systems and Evaluating Parameters:

Numerous methods have been considered for attitude control of space vehicles. A survey of these techniques is contained in References 1, 2 and 3. Most prominent among those used to date for active type systems have employed the mass expulsion principle or have been of the inertial type.

As previously explained, in evaluating the potential of the positive displacement injector, application has been restricted to missions which would normally operate in a pulsing mode. It was further necessary to restrict the comparison to the more obviously competitive alternates and also to define the evaluation parameters considered significant to limit the scope of the study.

Inasmuch as the positive displacement injection principle is of the mass expulsion type, it is logical that the basic comparison should include consideration of other systems of this nature. This evaluation becomes even more appropriate based upon the existence of many systems of this type which provides a realistic measure of comparison. Theoretical performance analysis can be supplemented with practical limitations which in many cases significantly influence competitive selection. In addition to other mass expulsion systems, it is also however necessary to consider systems of the inertial type. The reaction wheel system has been used in this study as representative of this class in view of its advanced development and application.

The most significant general parameters used in selecting a reaction control system for an application are the total system weight to satisfy the mission requirements and reliability. These parameters and particularly the former have been used in this study. This does not mean to infer that the many other parameters required to optimize a selection can be neglected or would not in some instances override a system selection based upon weight and reliability considerations alone. However, a generalized treatment to establish feasibility of concept can be established using only these parameters while recognizing that eventual application to a particular mission must evaluate other factors such as state-of-the-art, lead time, compatibility with the environment and life requirements, envelope limitations, etc.

The mass expulsion type systems considered in this evaluation included cold gas, monopropellant, the conventional bi-propellant system and electric propulsion techniques.

(2) Assumptions Required for Evaluation:

A set of assumptions was made and system weight estimates calculated. The major assumptions or considerations are described below:

a. Systems of the various types would be estimated for various total impulse requirements from 100 to 500,000 pounds-seconds. As systems become obviously non-competitive on a weight basis further computations would not be made. In the case of the electric propulsion and bi-propellant systems the requirement was later extended to 1,000,000 pound-seconds.

b. A pulsing mode of operation was specified and an assumed degradation in theoretical performance based upon available data applied. For instance, it was assumed that bi-propellant performance would be 80% of theoretical performance operating at pulse widths of the order of ten milliseconds. (Note: Actual degradation is dependent upon pulse frequency and thrust level in addition to pulse width. The 80% of theoretical performance used in this analysis is thus only applicable to a particular set of conditions; typical pulse width, duty cycle and thrust level. For other conditions a different figure would be required).

c. Nitrogen gas was used as representative of the cold gas systems, 90% hydrogen peroxide for the monopropellant systems and the basic comparison for the bi-propellant systems was made for the nitrogen tetroxide - 50% hydrazine - 50% UDMH propellant combination.

d. Other detailed parameters such as tankage safety factors, shape, material properties, storage pressures consistent with the system under consideration were specified.

e. A direct comparison in the terms used for the mass expulsion systems was not possible considering the reaction wheel concept. Further assumptions in terms of vehicle size and inertia were required and a restriction placed on the nature of disturbances compensated.

(3) Results of Analysis:

As initially analyzed, operation of the positive displacement injection system was similar in principle to that of a conventional bi-propellant system. That is, the injector would provide propellant to the chamber over a pulse duration of the order of ten milli-seconds as would be the case for a conventional system using solenoid valve control. It was anticipated that the bi-propellant system would satisfy a range of total impulse requirements and that the injector principle would be superior to the conventional system for a portion of this range based upon a number of considerations such as:

a. Using the positive displacement injector allows use of a low pressure propellant feed system with a resulting reduction in tankage and line wall thicknesses and hence lower weight. The low pressure feed system is possible in that the increase in propellant pressure takes place in the injector rather than in the propellant tanks.

b. An improvement in the accuracy of the impulse bit and O/F ratio should result in a reduced propellant requirement. As the total impulse requirement increased, such effects were expected to overcome the slightly heavier weight of the injector compared to the conventional system's valving and thus reflect a superiority of this system on a weight basis.

The first approach to the system comparison evaluation is presented on Figure 12. Basically, the conclusions drawn from this analysis were:

a. Application of a bi-propellant system will result in the minimum weight chemical mass expulsion system over a wide range of total impulse requirements.

b. Inertial type systems on a weight basis can be very competitive providing requirements are compatible with saturation limitations of this device and are not of very high torque magnitude. This result suggests that this system combined with a mass expulsion system for desaturation and for high impulsive perturbations would produce an optimized arrangement for some applications.

c. Consideration of the potential of the positive displacement injection principle can be restricted to detailed comparison to the conventional bi-propellant system.

   That is, bi-propellant systems of the conventional or PDI type appear optimum for a wide range of total impulse requirements. The alternative systems considered would not be weight competitive to either of these systems over this range. Thus, detailed consideration of systems in this range can be limited to systems of the bi-propellant type.

   The comparative analysis of the PDI and conventional bi-propellant system has thus been considered in detail with respect to each other. This comparison including consideration of additional propellant combinations to the basic N_2O_4-50% UDMH, 50% N_2H_4 is contained in Section C.

d. Propellant represents the predominant system weight element for the higher system total impulse requirements.

e. The weight of a bi-propellant system using conventional valving or the PDI concept is substantially the same.

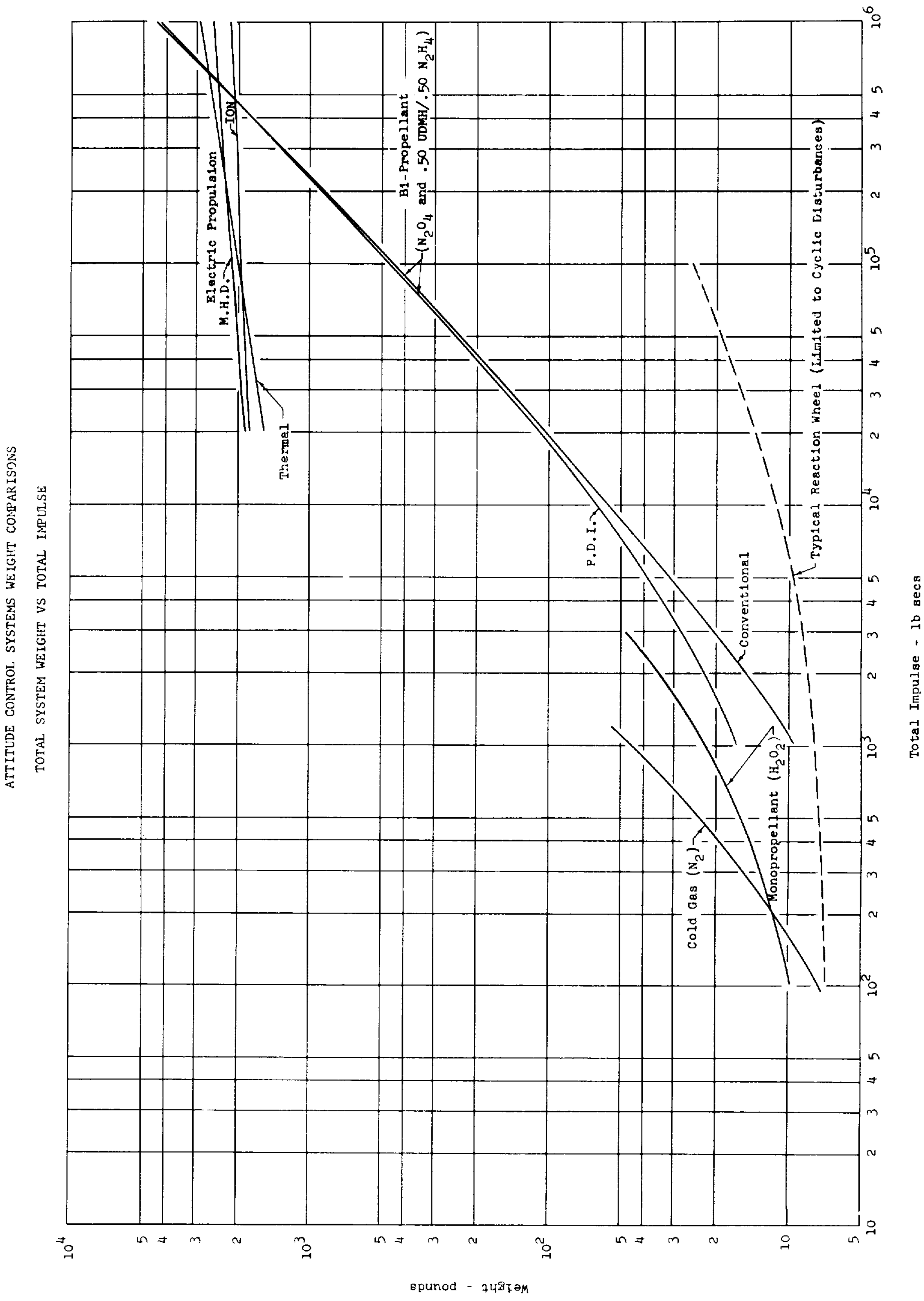

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Figure 12

(4) Comments on Other Systems Analyzed:

The comparative analysis, in addition to the bi-propellant systems, considered nitrogen gas, 90% hydrogen peroxide monopropellant, various types of electric propulsion systems and a reaction wheel system. The potential and limitations of these alternate systems is commented on below.

a. Cold Gas System

A cold gas system is restricted to a low value in terms of total impulse by virtue of its poor density impulse. It possesses a number of other characteristics favorable to its selection beyond a weight consideration which has resulted in its extensive application to date. Among these are its simplicity, advanced development and low cost. Thermal problems associated with the hot gas systems are also non-existent. It is furthermore capable of operating at extremely low thrust levels and impulse bits with virtually no limitation on the lower magnitude of either.

This system thus deserves serious consideration for either a pulsing or steady state requirement as long as the total impulse magnitude is not sufficiently high as to impose an unacceptable weight penalty. Unfortunately this limitation occurs at very low values. Practical engines operating with cold gas are also limited to fairly low values of thrust. Usually, however, high thrust levels are also associated with high total impulse requirements and thus the system would have already been excluded from consideration on this basis. Continued extensive use of this type system is to be expected for the smaller scientific payload type of mission.

b. 90% Hydrogen Peroxide Monopropellant System

Hydrogen Peroxide was selected as the propellant to be used in this comparison in view of its extensive application and capability of catalytic decomposition. It was selected rather than other propellants with higher specific impulse because of the relative simplicity of this system. Other monopropellants in terms of handling or initiation of decomposition can be more complex than a bi-propellant system and still not be capable of achieving a comparable specific impulse.

The monopropellant system studied is limited to relatively low total impulse applications in view of its low specific impulse. For pulsing operation this system is poor considering the relatively long delay in initiating decomposition (References 1 and 6). It would show to somewhat greater advantage for a system requiring long duration pulses but on a weight basis would still be restricted to low values of total impulse, the order of several thousand pound-seconds.

c. Electrical Propulsion Systems

Electrical propulsion systems were also investigated. Considering present day technology, application of such systems for attitude control appears limited to very high total impulse requirements mainly due to the high weight of the power supply required. Continuing development will undoubtedly result in substantial reductions in the weight of power supplies per kilowatt which will improve the competitive position of this type of system.

d. Reaction Wheel System

Inertia wheel and propellant utilizing systems do not directly lend themselves to a comparison unless it is for a specific vehicle and mission with all control requirements completely defined. In investigating the potential of this type of system it was necessary to make some additional assumptions to determine the relative potential of this class of systems.

After defining a vehicle in terms of size and other parameters, notably satellite moment of inertia, the control system was investigated based on capability of correcting external disturbances of constant torque and between stable limits or not subjected to external disturbances of a non-cyclical nature. The investigation indicated that the weight of an inertial wheel system is prohibitive if it must correct unidirectional torque of appreciable magnitude and is not complemented with a mass expulsion or other system capable of desaturating the wheels. The nature of this type correction is such that for every increment of impulse expended, the angular velocity of the flywheel increases by an equivalent amount. Minimum weight for such a system can be established using the hoop stress of a simple hollow cylinder rotating about its centroidal axis to determine saturation speed. The imposition of the requirement for uni-directional torque capability does not permit a feasible system.

On the other hand, for cyclic disturbances or limit cycle operation the system based on the assumed vehicle appeared very attractive on a weight basis. This has been seen on Figure 12.

Such a result suggests combining this type of system with a mass expulsion system for many types of applications. The mass expulsion system provides capability for uni-directional torquing requirements and also for desaturation of the reaction wheels. The wheels in turn provide a light weight system for counter-acting disturbances of a cyclic nature or for limit cycle operation. Such a combination has, in fact, found favor in many applications as can be seen in the survey results (Appendix A).

(5) Reliability Considerations:

In addition to investigating the weight of the two types of bi-propellant systems, relative reliability was considered as an evaluation parameter.

A reliability analysis was thus performed to compare the PDI to a conventional solenoid valve arrangement. The results indicated a negligible difference between the two concepts. The failure mode analysis is shown in Appendix K.

The reliability comparison was restricted to a consideration of the injector contrasted to a pair of valves or dual pintle valve required by a conventional system in that either system will require essentially a like number and kind of other components. The basic difference is thus restricted to the flow control device.

Several considerations which would favor use of the injector are not reflected in the analysis. These include:

a. The injector solenoid valve will be more remote from the chamber heat source than would valving for the conventional pulse engine.

b. The injector solenoid valve will be handling nitrogen gas rather than propellant. The latter normally presents a more severe operating condition.

Derating factors were not available to reflect these more optimum operating conditions and thus a quantitative evaluation of their effect was not possible.

The Failure Mode Analysis was based on the pressure actuated piston type design. It is however also representative of the other PDI designs considered though minor changes would result in the failure rates for each. For example, use of the port type design, which would allow removal of the check valves preventing propellant leakage back to the supply during pressurizing stroke, would result in slight improvement in the reliability estimate.

C. Comparison of PDI and Conventional Bi-Propellant Systems

Details of the analysis of the PDI and conventional systems used in the comparative systems evaluation are considered in this section. In addition to the basic propellants, other combinations were investigated. The effect of propellant selection on system weight is illustrated. Modifications to the injector analysis required by the various propellant combinations were also determined and are outlined.

(1) Systems Weight Analysis:

A systems weight analysis was performed to compare PDI to the conventional bi-propellant system. The gas actuated piston type PDI was used for this study.

The design criteria previously described was used as the basis for the weight analysis. The propellant combination N_2O_4 - 50% UDMH, 50% N_2H_4 was used for the study. Two other propellant combinations, O_2 - H_2 and OF_2 - B_2H_6 were also investigated to determine their effect on system weight. The O_2 - H_2 combination is cryogenic and OF_2 - B_2H_6 combination a space storeable cryogenic. Storeability of these propellants was not considered in this analysis; i.e. it was assumed that propellant supplied to the injector was in the liquid state. These combinations were used because they fairly represent the three classes of propellants, earth storeable, deep cryogenic and mild or space storeable cryogenic.

System total impulses of 1000, 10,000, 100,000 and 1,000,000 lb-sec and corresponding impulse bits of 0.1, 0.5, and 1.0 lb-sec were analyzed. Chamber pressures for these total impulses were optimized for minimum system weight for both the PDI and the conventional system. These optimum chamber pressures (Appendix D, Figure D2) were used for the weight study.

Results of the weight analysis for the N_2O_4 - 50% UDMH 50% N_2H_4 propellant combination are shown in Tables 2 and 3. They show the PDI slightly heavier than the conventional system in the range of 1000 to 20,000 lb-secs total impulse. At these low total impulses the PDI injector is heavier than that for the conventional bi-propellant system. The propellant volume is small, therefore, propellant tanks for both systems are at minimum thickness despite the higher tank pressure in the conventional system. Therefore, the PDI system gains no weight advantage due to the low pressure feed at these low total impulses.

From 20,000 to 1,000,000 lb-secs the weight difference between the PDI and conventional bi-propellant systems is negligible. The low optimum chamber pressure (50 psi) at these high total impulses, considerably reduces the weight advantage of the PDI propellant feed system over that of the conventional system. PDI tankage weight could be lowered by lowering the propellant storage tank pressure below 80 psi. The 80 psi tank pressure was used to obtain a temperature range of 40°F to 140°F for the N_2O_4 - 50% UDMH/50% N_2H_4 propellant combination. The weight advantage of the PDI system is further offset by the increased nitrogen gas requirement for actuating the PDI pistons. Nitrogen gas requirements are discussed in Appendix D. The net effect is a negligible weight difference between the two systems.

An analysis (Appendix G) was performed to investigate the effect of O/F ratio and impulse bit accuracy on system weight for both the PDI and conventional bi-propellant systems. The results are shown in Table 4. The more accurate O/F ratio and impulse bit control of the PDI gives it approximately a 3% system weight advantage over the conventional system between 100,000 lb-sec and 250,000 lb-sec total impulses. At the lower total impulses (1000 lb-sec to 10,000 lb-sec) the PDI system is heavier than the conventional system despite better O/F ratio and impulse bit accuracy.

Table 5 shows the results of the weight analysis of a PDI system for the two alternate propellants, O_2 - H_2 and OF_2 - B_2H_6. A total impulse of 100,000 lb-sec and impulse bit of 0.5 lb-sec were investigated. The O_2 - H_2 and OF_2 - B_2H_6 systems showed weight improvements of approximately 23% and 20% respectively, over the N_2O_4 - 50% UDMH, 50% N_2H_4 system. The major portion of the weight saving is due to the higher specific impulses of these propellants.

The advantage to be gained in terms of reduced system weight by use of the high energy propellants is quite evident. However, considering the cryogenic nature of these combinations the system weight saving for many missions may be offset by insulation requirements and "boil-off" losses. An attitude control system with a high total impulse requirement usually will represent a mission of extended duration; (particularly if the system is compatible with a pulsing mode of operation); thus, storage considerations would be significant to propellant selection. The indicated space storage characteristics of the mild cryogenics such as OF_2-B_2H_6 makes it appear that the potential of such a combination applied to the PDI for attitude control is much greater than combinations such as O_2 - H_2.

It is concluded from the system weight analysis that at high total impulses (100,000 to 1,000,000 lb-sec) hardware weight is 10% to 15% of the system weight. Therefore, the potential weight savings that can be made in hardware is small compared to the total system weight. It is apparent that improved propellant consumption would cause a considerable system weight saving since propellant is the main weight element of the system.

SYSTEM WEIGHT

Positive Displacement Injection

N_2O_4 - 50% UDMH/50% N_2H_4

Description	Impulse bit, lb-sec	0.1	0.5	1.0	1.0
	Thrust, lbs.	10	50	100	100
	Total impulse, lb-sec	10^3	10^4	10^5	10^6
	Expansion ratio	40	40	40	40
	Chamber pressure, psi	200	200	50	50
	Tank pressure, psi	80	80	80	80
	80% Theoretical Isp, sec.	254	254	250	250
Weight, lbs.	8 Thrust chambers	.5	2.0	6.0	6.0
	8 Injectors	9.6	12.5	16.9	16.9
	Propellant tanks	.3	1.6	6.0	60.0
	Expulsion bladders	.1	.5	2.0	9.5
	Propellant	3.9	39.4	400.0	4000.0
	Gas + gas tank	.6	4.6	30.0	300.0
	Lines	.5	1.3	2.5	4.1
	Controls	1.0	1.0	1.0	1.0
	Total	16.5	62.9	464.4	4397.5

Table 2

SYSTEM WEIGHT

Conventional Valving

N_2O_4 - 50% UDMH/50% N_2H_4

Description	Impulse bit, lb-sec	0.1	0.5	1.0	1.0
	Thrust, lbs.	10	50	100	100
	Total impulse, lb-sec	10^3	10^4	10^5	10^6
	Expansion ratio	40	40	40	40
	Chamber pressure, psi	200	150	50	50
	Tank pressure, psi	384	334	234	234
	80% Theoretical Isp, sec.	254	253	250	250
Weight, lbs.	8 Thrust chambers	.5	2.0	6.0	6.0
	8 Injectors	2.7	8.2	16.4	16.4
	Propellant tanks	.3	2.5	15.0	160.0
	Expulsion bladders	.1	.5	2.0	9.5
	Propellant	3.9	39.6	400.0	4000.0
	Gas + gas tank	.3	2.0	14.0	145.0
	Lines	.5	1.3	2.5	4.1
	Controls	1.0	1.0	1.0	1.0
	Total	9.3	57.1	456.9	4342.0

Table 3

EFFECT OF O/F RATIO AND IMPULSE BIT ACCURACY ON SYSTEM WEIGHT

I_b lb. sec.	I_T lb. sec.	P.D.I. W lbs.	P.D.I. W+ΔW lbs.	Conventional W lbs.	Conventional W+ΔW lbs.
.1	1,000	16.5	16.9	9.3	9.8
.5	10,000	62.9	67.0	57.1	61.6
1.0	100,000	464.4	503.4	456.9	522.8
1.0	250,000	1121.0	1218.5	1094.5	1257.3

ΔW = Increased system weight based on O/F ratio control and impulse bit repeatability.

Table 4

SYSTEM WEIGHT

Positive Displacement Injection

Alternate Propellants

Description	Propellants	O_2 - H_2	OF_2 - B_2H_6
	Impulse bit, lb-sec	0.5	0.5
	Thrust, lbs.	50	50
	Total impulse, lb-sec	10^5	10^5
	Expansion ratio	40	40
	Chamber pressure, psi	50	50
	Tank pressure, psi	15	15
	80% Theoretical Isp, sec.	342	317
Weight, lbs.	8 Thrust chambers	3.2	3.2
	8 Injectors	12.5	12.5
	Propellant tanks	6.1	5.5
	Expulsion bladders	2.0	2.2
	Propellant	292.0	316.0
	Gas + gas tank	34.2	26.0
	Lines	2.0	2.0
	Controls	1.0	1.0
	Total	353.0	369.0

Table 5

(2) Dynamic Analysis (Various Propellant Combinations):

In support of the system weight analysis described above, analysis of the PDI dynamics was conducted. The results of this analysis are summarized below and on Figures 13 - 15 which show the response and nitrogen requirements for the PDI for the following Propellant combinations:

N_2O_4 and 50% UDMH, 50% N_2H_4

O_2 and H_2

OF_2 and B_2H_6

The figures are based on the following conditions:

0.5 lb. sec.	Impulse Bit
50 psi	Combustion chamber pressure
300 psi	Nitrogen supply pressure
50 lb/in	Spring rate
0.025 in.	Pilot valve orifice diameter

The volume of the space between the top of the piston and the valve orifice = 0.1 (actuator piston area)

Spring preload = 0

Specific impulse for pulse operation = 0.8 (theoretical Isp)

Propellant Combination	Isp for Pulse Operation Sec.	O/F Ratio	Propellant Weight Per Pulse Lb.	Propellant Feed Presure Psi	P.D.I. Stroke In.	Actuator Piston Area In.^{2}	Weight of Nitrogen Used Per Pulse Lb.
N_2O_4 - 50% UDMH, 50% N_2H_4	253	1.4	.001978	80	.24	.21	.0000612
H_2 - O_2	342	3	.001462	15	.255	.26	.0000789
OF_2 - B_2H_6	317	3	.001578	15	.24	.182	.0000528

RESPONSE VS ACTUATOR PISTON AREA

P.D.I. - 0.5 Lb. - Sec. Impulse Bit
(N_2O_4, 50-50 N_2H_4 - UDMH)

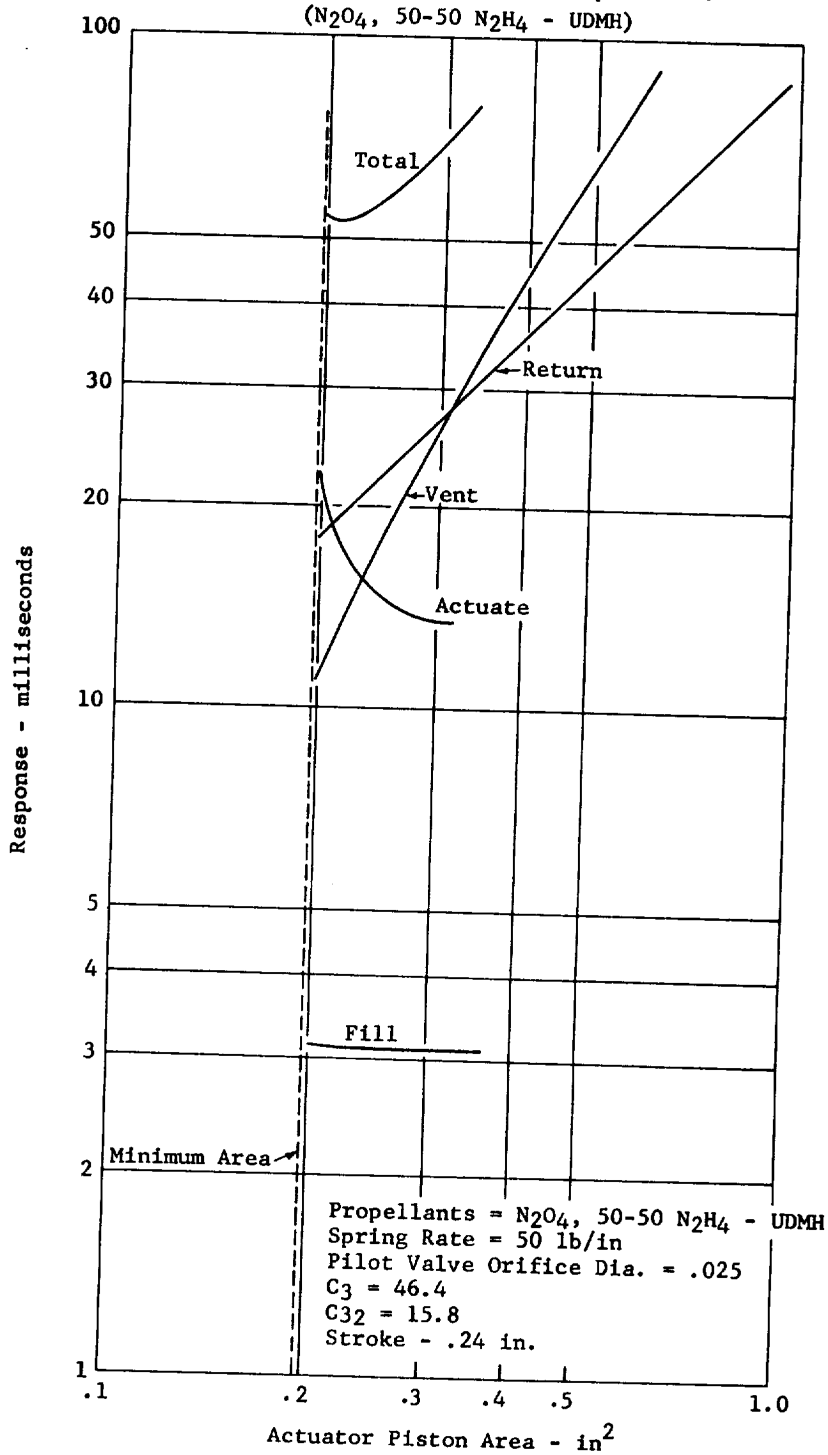

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Figure 13

RESPONSE VS ACTUATOR PISTON AREA

P.D.I. - 0.5 Lb-Sec Impulse Bit
(H_2, O_2)

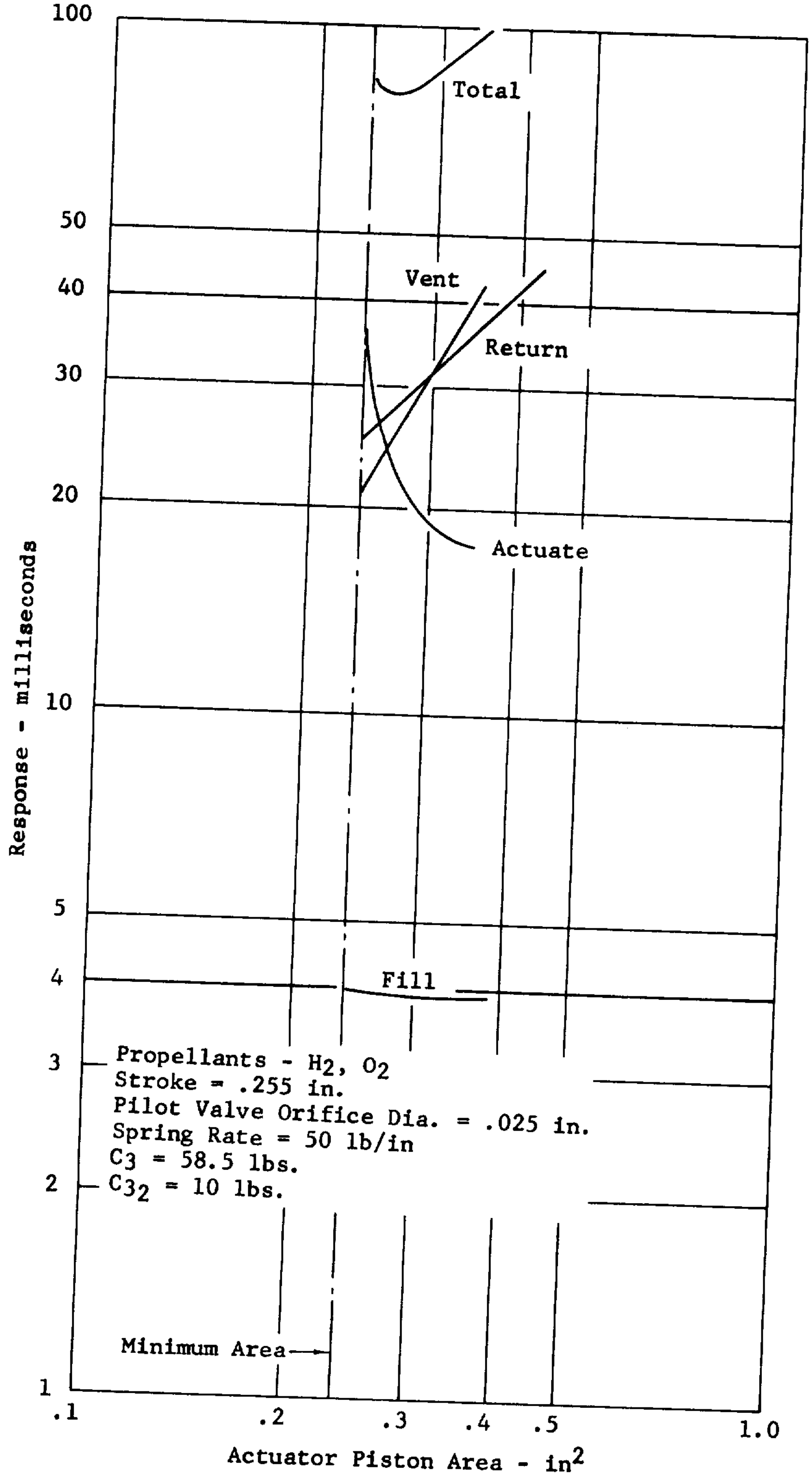

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Figure 14

RESPONSE VS ACTUATOR PISTON AREA

P.D.I. - 0.5 Lb. - Sec. Impulse Bit
(OF_2 & B_2H_6)

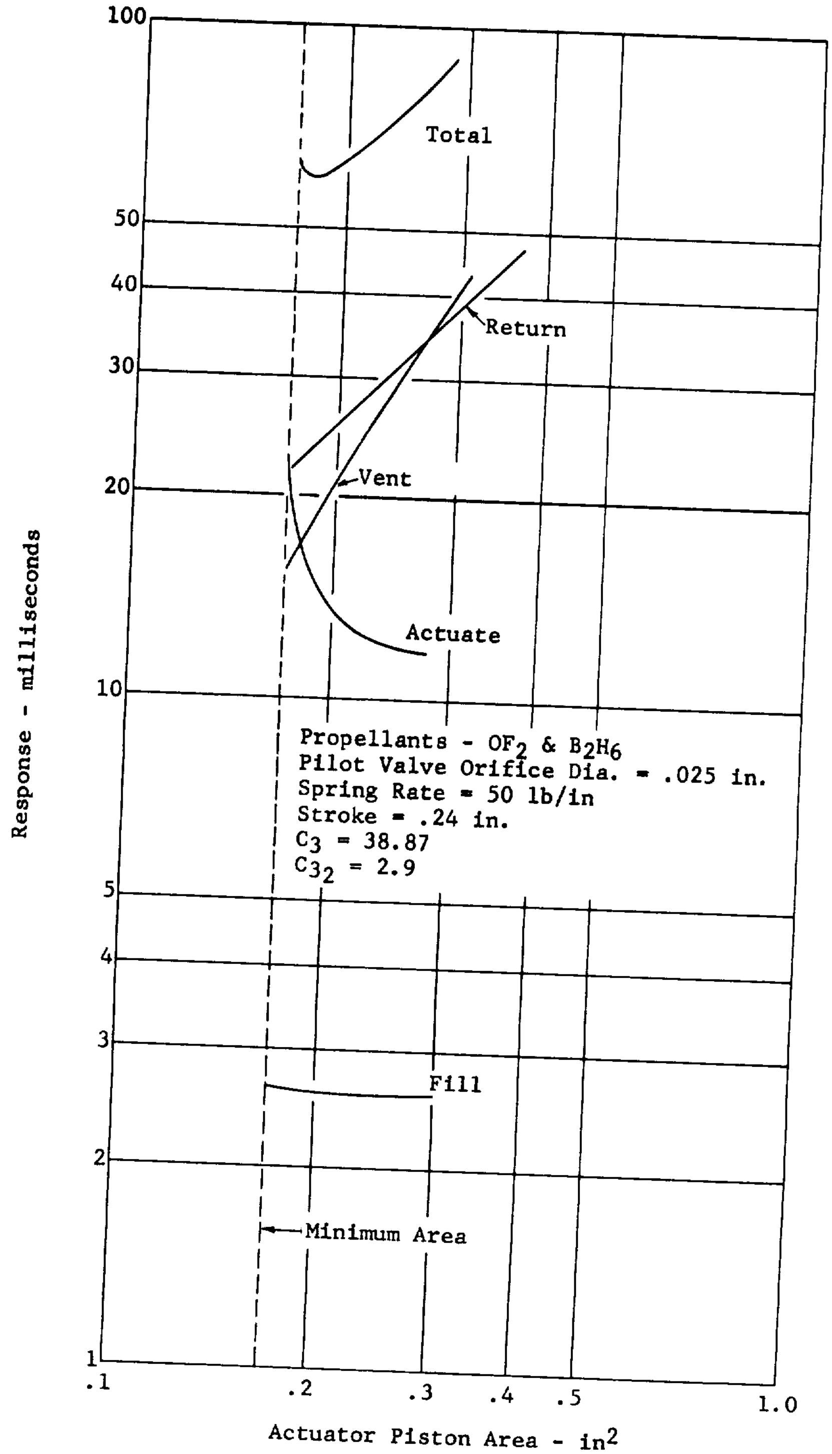

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Figure 15

D. <u>High Performance PDI</u>

The potential of the bi-propellant system approach had been established. Operation of the positive displacement injector at normal chamber pressures however did not indicate any particular superiority over the conventional bi-propellant approach.

The relative importance of propellant contribution to overall system weight was also clearly evident. The PDI was thus examined for possible potential of improving propellant performance.

Rocket propulsion performance may be improved by increasing the specific impulse of a propellant combination. The obvious methods for increasing theoretical performance are to increase engine chamber pressure and nozzle expansion ratio. Conventional bi-propellant pulse engines usually operate at low chamber pressures in order to minimize overall system weight. Thus, expansion ratios of these engines are usually in the order of 40:1 due to envelope limitations.

The PDI system may be operated at extremely high chamber pressures (5000 psi order of magnitude) without attendant propellant tankage weight penalty. A technique of rapid propellant injection is used. The entire propellant slug is injected prior to ignition (within 0.002 to 0.003 sec). This reduces actuating gas consumption since injection is accomplished against low chamber back pressure.

The increased chamber pressure results in an engine of considerably reduced size, therefore, expansion ratio is virtually unlimited by envelope requirements. Figure 16 shows the relative sizes of two 100 lb. maximum thrust pulse engines. One engine is based on 50 psi chamber pressure and 40:1 expansion ratio, and the other on 5,000 psi chamber pressure and 200:1 expansion ratio.

Specific impulse may be increased approximately 6% to 10%, depending upon the propellant combination, when chamber pressure and expansion ratio are increased from 50 psi to 5000 psi and 40:1 to 200:1 respectively. Table 6 shows the results for four propellant combinations. Normally, the increase in expansion ratio rather than increased chamber pressure is the predominant factor in improved specific impulse; the actual relative contribution being a function of the propellant combination under consideration. These increases in specific impulse represent substantial weight savings for systems of relatively high total impulse. Table 7 shows a weight breakdown of the high pressure PDI system for various total impulses using the N_2O_4 - 50% UDMH, 50% N_2H_4 propellant combination. Table 8 compares these weights to those for

100 LB THRUST CHAMBERS

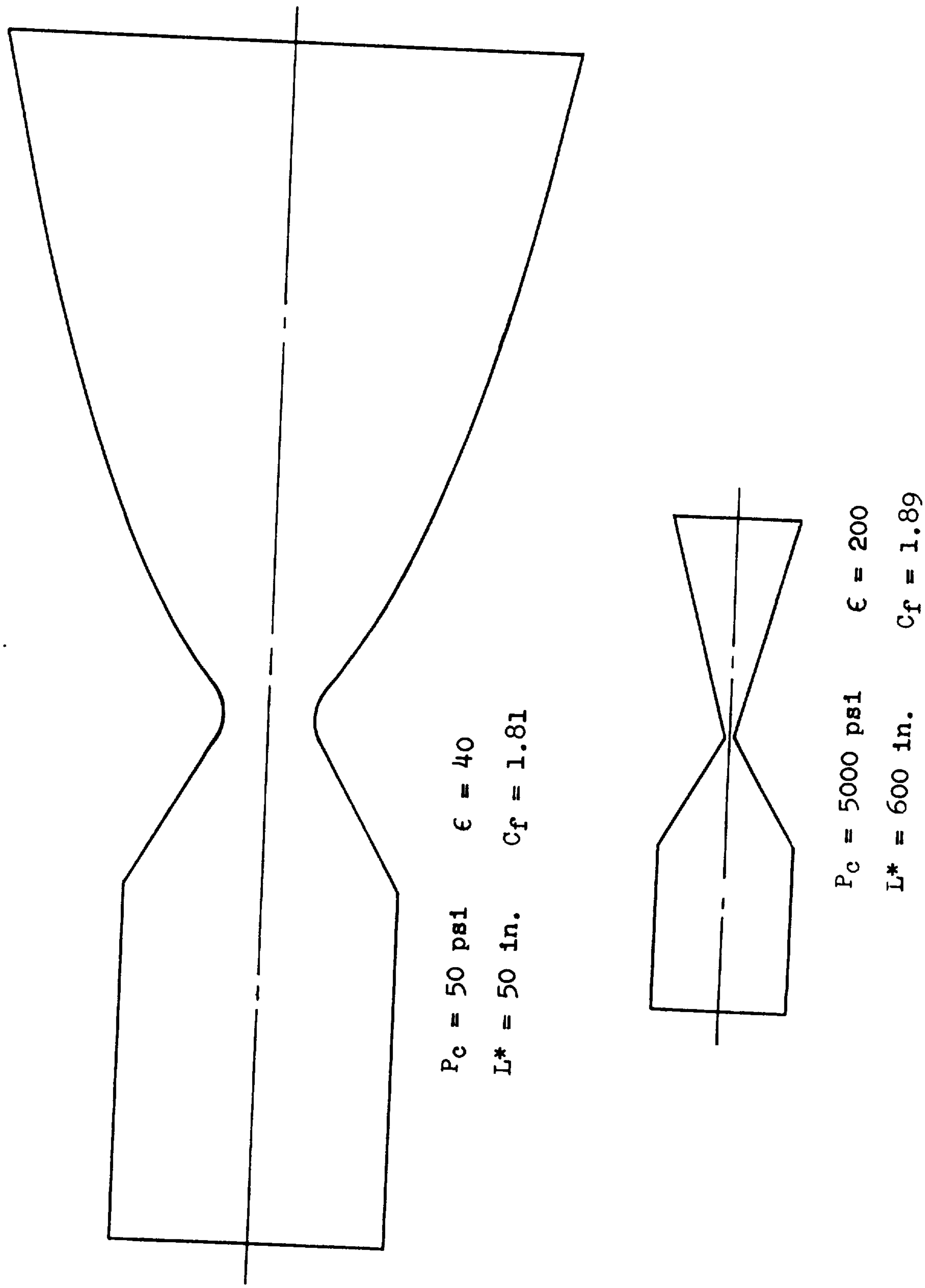

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Figure 16

HIGH PRESSURE POSITIVE DISPLACEMENT INJECTION

PROPELLANT PERFORMANCE COMPARISON

Propellant Combination	Theoretical Isp. Sec.		Percent Increase
	P_c=50 ϵ=40	P_c=5000 ϵ=200	
N_2O_4 - .50 UDMH/.50 N_2H_4	313	337	7.5
O_2 - H_2	428	449	5.5
OF_2 - B_2H_6	396	437	10.0
N_2O_4 - UDMH	305	333	9.0

Table 6

SYSTEM WEIGHT

Positive Displacement Injection

High Pressure

N_2O_4 - 50% UDMH/50% N_2H_4

Description	Impulse bit, lb-sec	0.1	0.5	1.0	1.0
	Thrust, lbs.	10	50	100	100
	Total impulse, lb-sec	10^3	10^4	10^5	10^6
	Expansion ratio	200	200	200	200
	Chamber pressure, psi	4000	4000	4000	4000
	Tank pressure, psi	80	80	80	80
	80% Theoretical Isp sec.	270	270	270	270
Weight, lbs.	8 Thrust chambers	1.0	4.0	12.0	12.0
	8 Injectors	9.6	12.5	16.9	16.9
	Propellant tanks	.3	1.6	5.6	56.0
	Expulsion bladders	.1	.5	1.9	9.5
	Propellant	3.7	37.0	370.0	3700.0
	Gas + gas tank	.2	1.8	18.8	188.0
	Lines	.5	1.3	2.5	3.4
	Controls	1.0	1.0	1.0	1.0
	Total	16.4	59.7	428.7	3986.8

Table 7

SYSTEM WEIGHT COMPARISON

Injection System	Weight, lbs.			
	$I_T = 10^3$	10^4	10^5	10^6
Conventional	9.3	57.1	456.9	4342.0
High Pressure Positive Displacement Injection	16.4	59.7	428.7	3986.8

Table 8

a conventional bi-propellant system using the same propellant combination. The high pressure PDI shows a 6% to 8% weight savings at system total impulses of 100,000 lb-sec to 1,000,000 lb-sec. The weight savings would be even greater for the OF_2-B_2H_6 and UDMH - N_2O_4 propellants based on the specific impulse data in Table 6.

An additional improvement in propellant consumption may be inherent in this system due to high combustion efficiency. This is discussed below.

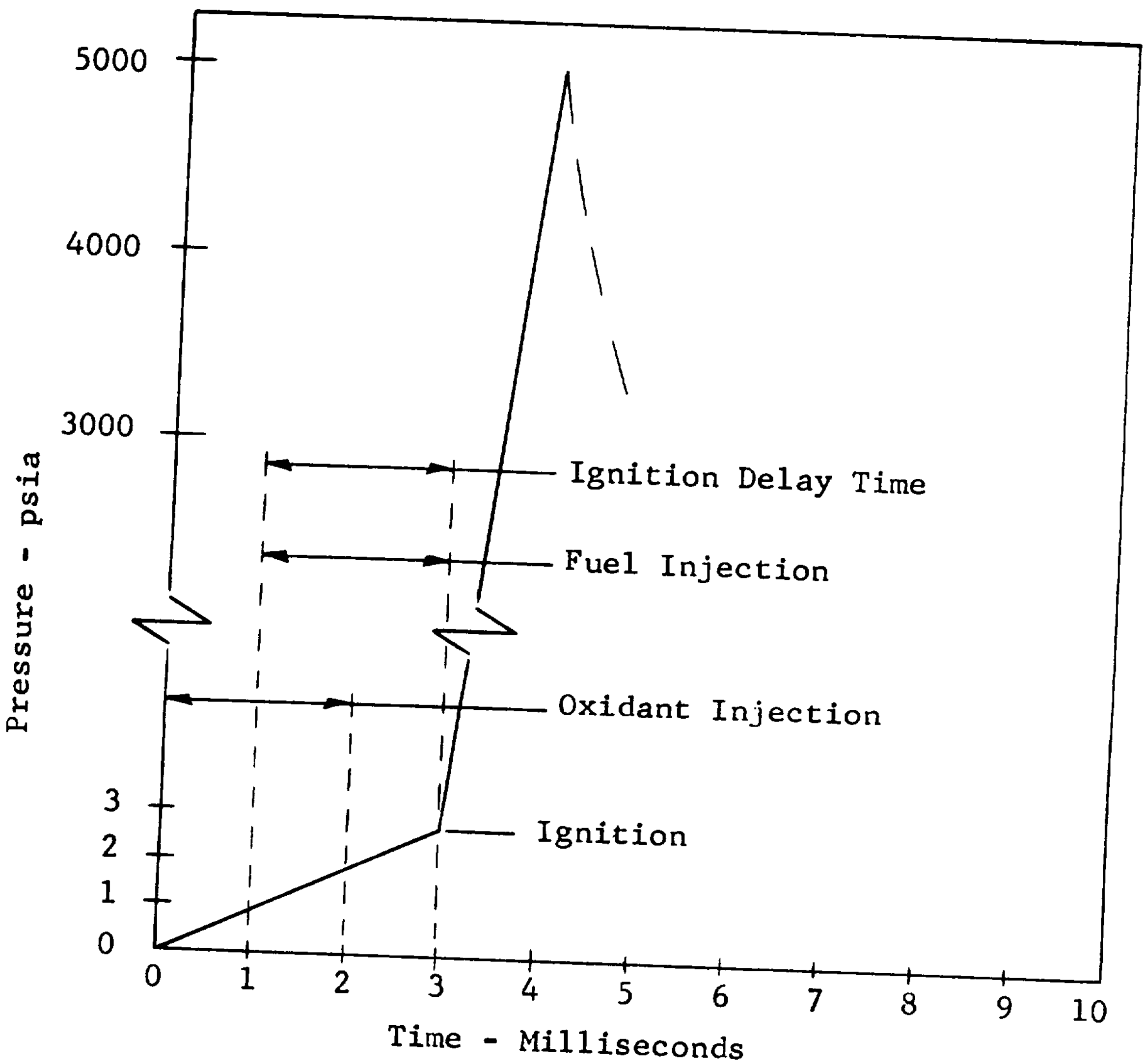
E. Ignition and Combustion

In this section, the ignition and subsequent combustion of the propellant using the high performance positive displacement injector concept is discussed. Design criteria for the preliminary design is given, and a short evaluation of the concept and the resulting pulse rocket motor design is made.

The positive displacement injector concept is essentially a scheme to "dump" propellants (nitrogen tetroxide and 50% UDMH, 50% hydrazine are considered for this discussion. A similar analysis would however apply for other propellant combinations) into a rocket chamber which is near zero pressure. The propellants then combine, ignite and combust causing the pressure in the rocket chamber to increase. Thrust is generated during the combustion process and during tail off. By suitable rocket motor design and operation, the specified impulse bit can be achieved. Since this system is capable of generating high chamber pressures, say of the order of 1000 to 5000 psi, then a well designed nozzle with a large expansion ratio should produce high Isp performance.

One of the main features of this scheme is to inject the propellants into the chamber while the pressure in the chamber is low. Adverse conditions would prevail if ignition and combustion occurred during the injection process. In order to prevent this situation from occurring, a propellant injection lag is introduced. The nitrogen tetroxide injection precedes that of the fuel. Time is allowed for the oxidizer to evaporate and then the fuel is injected as a fine spray. The time duration of the fuel injection is equal to the ignition delay time for this system. In addition, since the fuel is in a fine spray, it will combust entirely before any of it deposits on the chamber walls.

It is recognized that the chamber design and valve operation must be optimized. The necessary theoretical work to accomplish this end has been done. For a given rocket motor chamber size, the non-equilibrium evaporation rate of nitrogen tetroxide can be calculated (Reference 4). Thus the vapor pressure prior to combustion can be determined. This is an important factor since the ignition delay here is a function of the chamber pressure. The ignition delay time is determined as a function of pressure from the chemical kinetics (Reference 4). Now it is required to match the fuel injection time interval, which is determined from the valve dynamics, to the ignition delay time at a suitable vapor pressure. The start of the ignition delay time is the same as the start of the fuel injection. The sequence of events are shown qualitatively in the sketch below.



PROPELLANT INJECTION SEQUENCE IN A ROCKET MOTOR

Care must be taken that the fuel injection time interval is not greater than that of the ignition delay time, for then fuel injection occurs against an increasing pressure environment. In addition, if the fuel injection time is much less than the ignition time, then an excessive loss of the propellants can occur through the nozzle. The optimum fuel droplet size for the given rocket motor can be determined from the droplet ballistics which was developed in Reference 5. One of the characteristics of pulse motors is the inability to attain high C* efficiency, a condition which reflects on the combustion processes. In order to relieve this situation, it is suggested that the droplet size be determined so that it would completely evaporate prior to reaching any chamber wall. This is one of the conditions which must be considered in determining the chamber geometry. During the fuel evaporation process an infinite range of oxidant-fuel ratios exist thus insuring combustion. In addition, due to the small droplet size and spray geometry heterogeneity and stratification can be minimized to give good C* efficiency.

The potential advantages of this high pressure, positive displacement injection system are the following:

a. Propellant loss is about 1% due to the small throat area, and the low pressures at which ignition occurs for this propellant combination.

b. As a result of the high chamber pressure, the size of the motor is small for the operating thrust level.

c. In addition, due to the high chamber pressure, a high C_f is obtained. Since the ambient pressure is very low, the nozzle with larger expansion ratio, will be operating in an unseparated regime for most chamber pressures, thus ensuring good performance for a pulsing engine.

d. Full use is made of the tail off part of the impulse cycle.

e. By optimizing propellant droplet size and chamber geometry, C* efficiencies approaching those of good steady state values are expected. This is so because the same droplet ballistics criteria is being used. In addition, because of high nozzle expansion ratio, it is suggested that high Isp efficiencies will ensue.

V POSITIVE DISPLACEMENT INJECTOR TEST PROGRAM

A test program designed to supplement the injector theoretical analysis was conducted as a part of this study effort. It was designed to evaluate the more critical performance areas of the Positive Displacement Injector.

A. Objectives

The basic objectives of this program were the following:

a. Evaluate the capability of a positive displacement injector to supply repeatable impulse bits of good accuracy.

b. Obtain data on the operating characteristics of this type of injector.

c. Compare the actual dynamics of the test injector with the theoretical analysis based on the equations of Appendix B.

This program was limited to the injector only.

B. Design Parameter Study

Before proceeding with the design of a test injector a study was made to determine the effects of various parameters on the response and nitrogen requirements for the pressure actuated type of injector. The results are shown in Figures 17 through 22 and are based on the following conditions:

a. I = Impulse Bit = 0.1 lb. sec.
Thrust = 10 lbs.

Isp = Specific Impulse = 320 seconds

Pc = Combustion Chamber Pressure = 400 psi

Pi = Propellant Injection Pressure = 480 psi
Volume of oxidizer per stroke = .003725 in.^{3}
Volume of fuel per stroke = .003725 in.^{3}
Volume of nitrogen per stroke = actuator piston area x (.05 + stroke)

b. The initial conditions for the injector were:

D_e = Equivalent orifice diameter of pilot valve = .0252 in.

P_s = Nitrogen supply pressure = 303 psi

A_a = Actuator piston area = .1955 in.^{2}

S = Stroke of piston = .124 in.

P_1 = Preload = 20 lbs.

K = Spring rate = 80 lb/in

A_p = Injector piston area = .03 in^2 per piston

F = Force opposing piston motion during actuating stroke (max.)

$$F = P_1 + KS + 2\,PiA_p$$

c. In order to keep the weight of the nitrogen required per stroke at a minimum, the force produced by the nitrogen on the actuating piston was kept at 1.01 F except for the case of actuating piston area vs. response. Thus $P_s\,A_a = 1.01F$, which resulted in changes in A_a when P_s or F were varied.

Figures 17-22 show that increasing the actuator piston area, preload, stroke or spring rate will increase the amount of nitrogen required per stroke, and that increasing the nitrogen supply pressure or pilot valve orifice diameter has no effect on it. The total cycle time decreased slightly as the actuator piston area or the preload increase above their minimum values, but it rapidly reaches a minimum value and then increases as they increase (Figures 17 & 18). Any increase in spring rate or stroke increases total cycle time (Figures 19 & 20), while increases in nitrogen supply pressure or valve orifice diameter decrease it (Figures 21 & 22).

C. Test Rig Mechanical Design

Using the knowledge of the effects of the various design parameters as a guide, a test rig (Figure 23) was designed and fabricated.

The test rig simulates a gas actuated piston type PDI. The main rig components are the gas piston, pump piston, pintle type poppet valve and valve seat, check valve, solenoid valve, piston and pintle sleeves, and the housing. The housing is designed to make all components and adjustments easily accessible. Provisions are included for varying piston stroke, pintle stroke, and piston and pintle spring preloads. This allows a complete test evaluation of the dynamic operating characteristics of the design. Therefore, correlation of the test results with the controls theoretical analysis is possible.

Close fits between the pump piston and sleeve and the poppet valve pintle and sleeve simulate an actual flight design. The sleeves are made removable to facilitate replacement in case they are damaged during testing. Teflon O-rings are used for dynamic sealing of the gas piston, pump piston rod, and poppet valve pintle. The materials selected for the rig design are compatible with the propellants used for the systems analysis and could be used in a flight design. Provisions are incorporated in the design for complete instrumentation necessary for measuring pressures, system response, and quantity of injected propellant.

D. Test Instrumentation

Figure 24 shows the test rig with the piston and pintle position transducers. Figure 25 is a schematic of the test instrumentation. The instruments used are as follows.

a. Hewlett-Packard model 202A Low Frequency Function Generator to provide the command signal.

b. McIntosh Lab. Inc. model P131 Switching Amplifier to provide the current to operate the solenoid valve.

c. Kister PZ 601 pressure transducers to measure the gas and fluid pressures.

d. A liner potentiometer to measure the piston motion.

e. Bentley P/U transducer to measure the pintle motion.

f. Allegany Instrument Co. model 512-A D. C. amplifiers to amplify the transducer signals.

g. Consolidated Electrodynamics Corp. Recording Oscillograph to record the transducer outputs.

RESPONSE VS ACTUATOR PISTON AREA

P.D.I., 0.1 Lb - Sec Impulse Bit

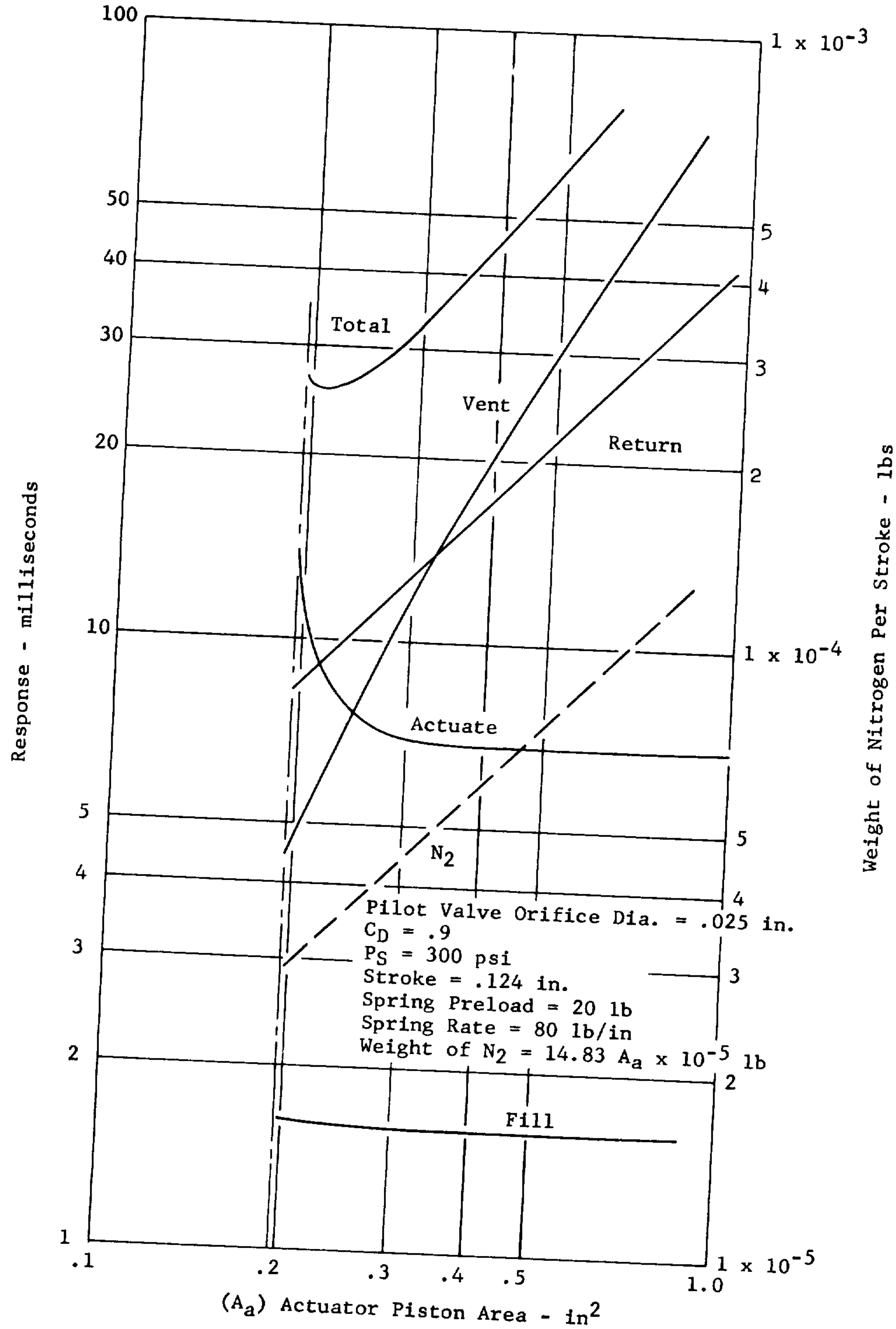


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Figure 17

RESPONSE VS SPRING PRELOAD

P.D.I., 0.1 Lb - Sec Impulse Bit

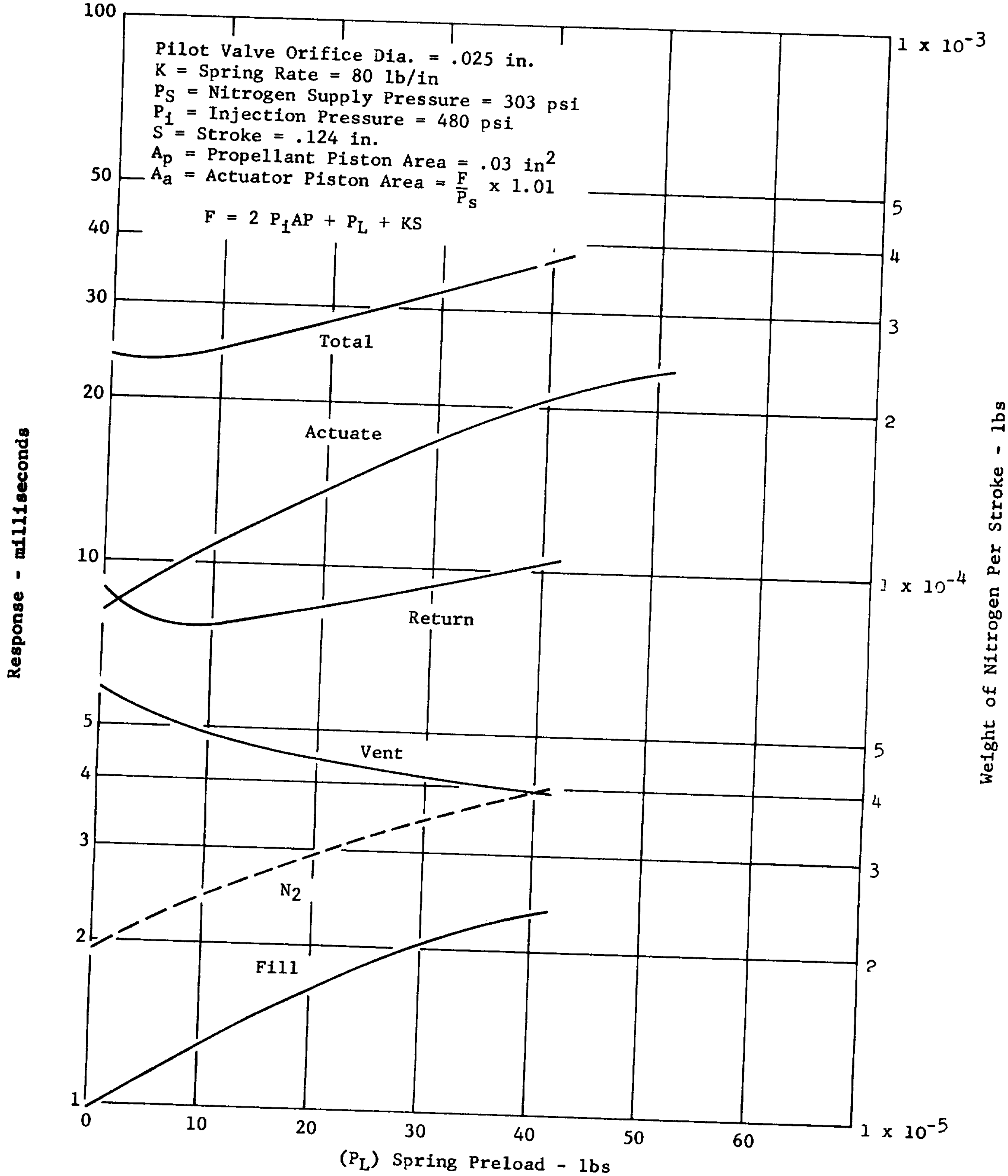

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Figure 18

RESPONSE VS SPRING RATE

P.D.I., 0.1 Lb - Sec Impulse Bit

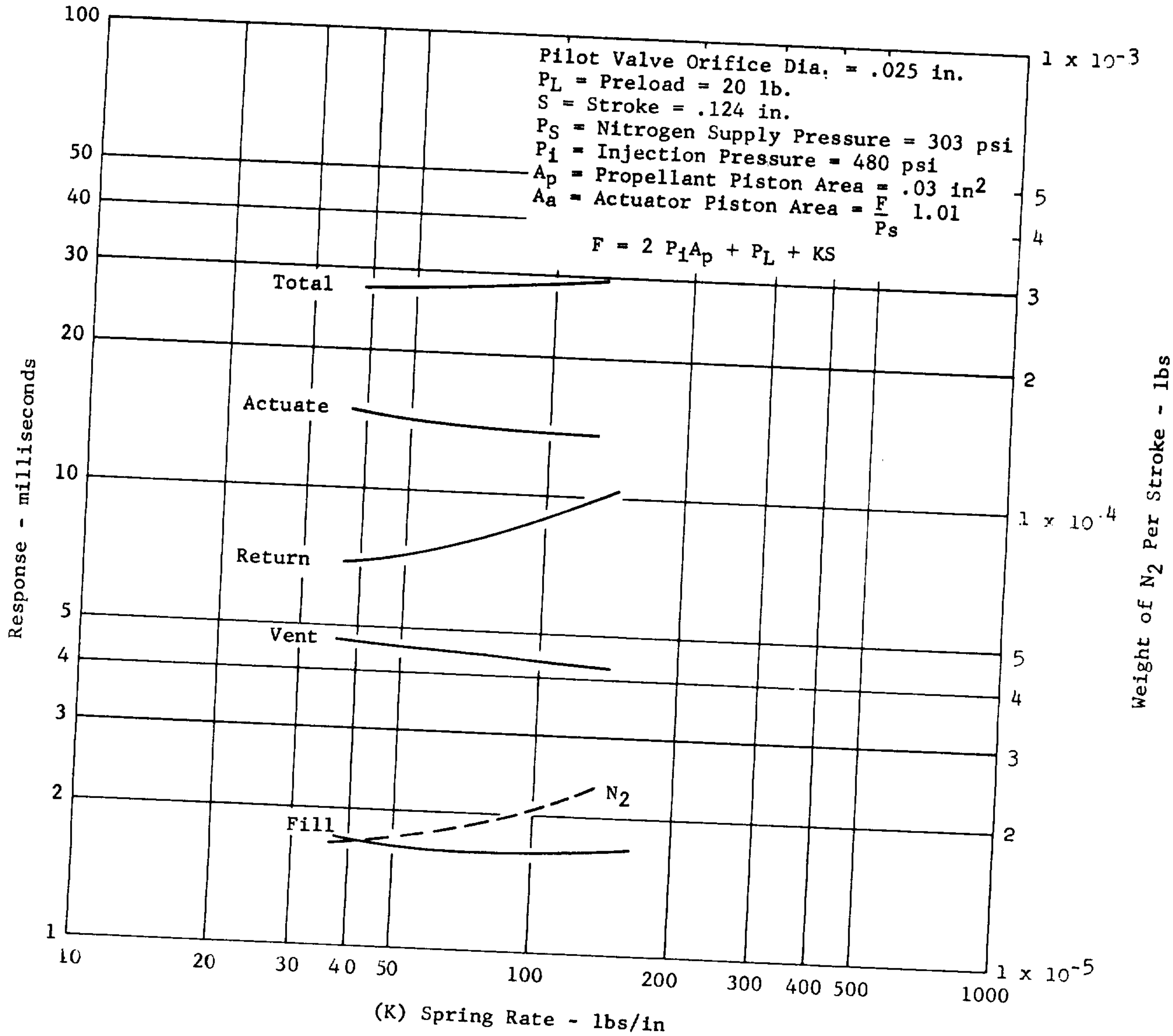

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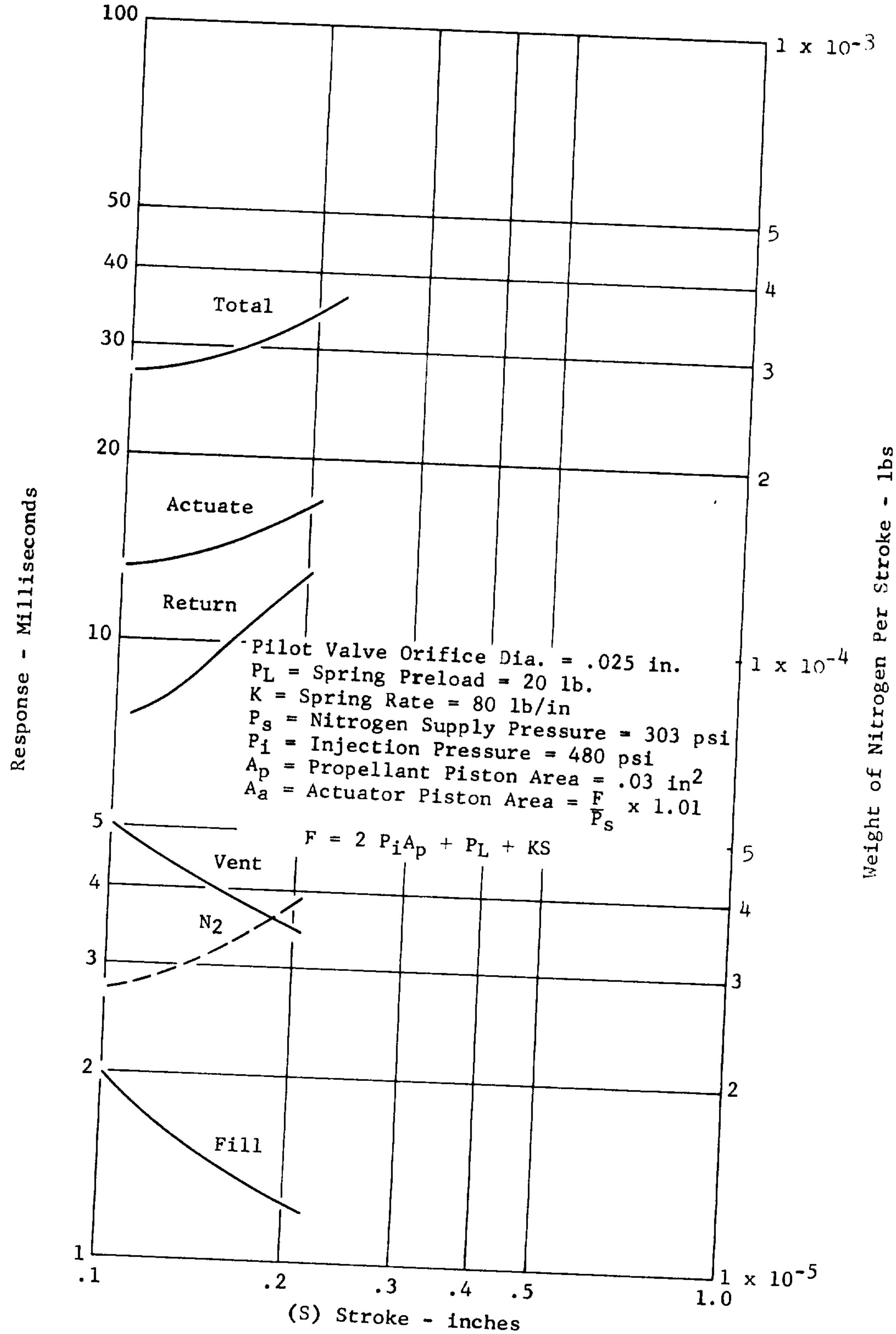
Figure 19

RESPONSE VS STROKE

P.D.I., 0.1 Lb - Sec Impulse Bit



3304

Figure 20

RESPONSE VS P_s

P.D.I., 0.1 Lb - Sec Impulse Bit

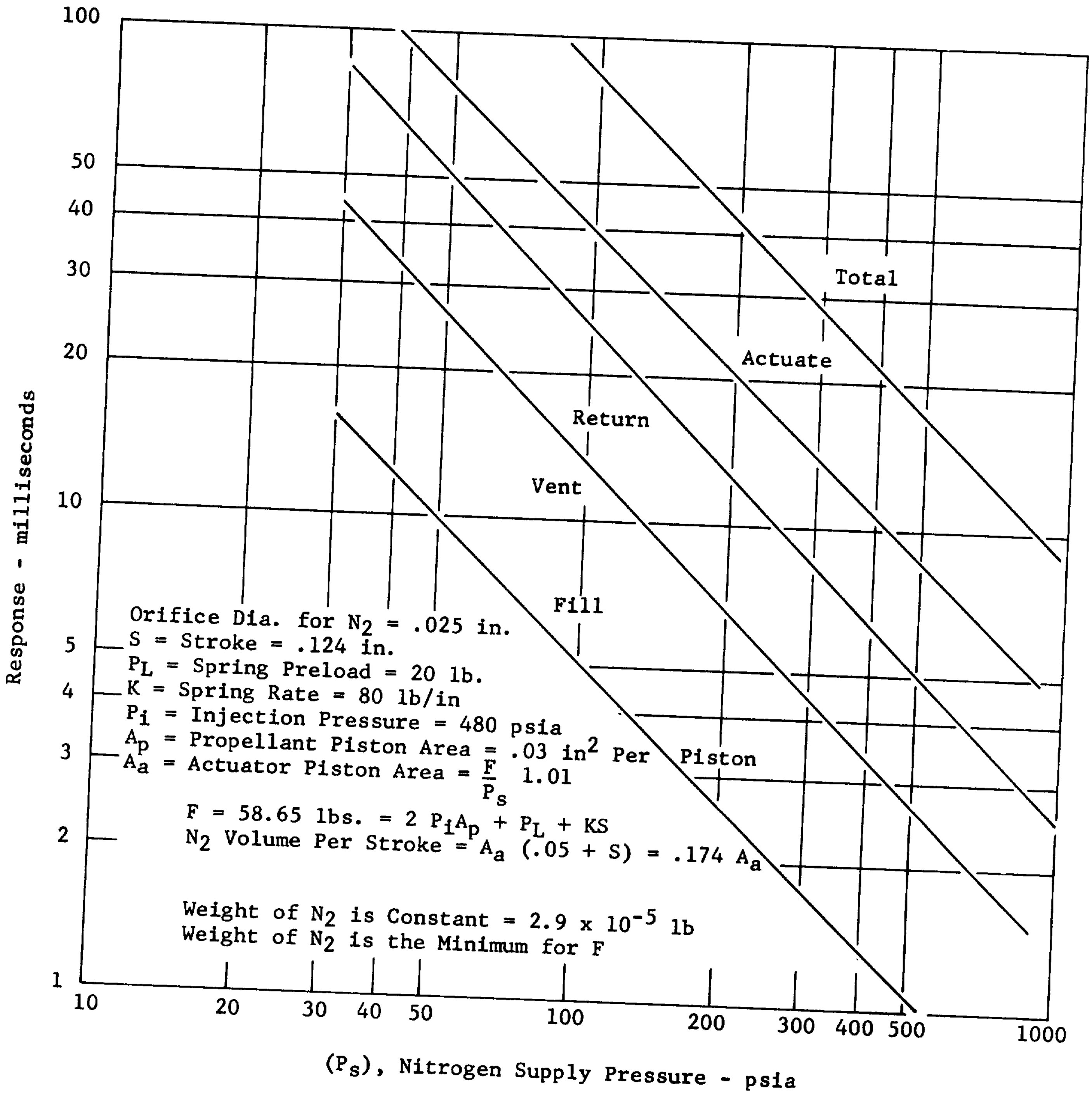


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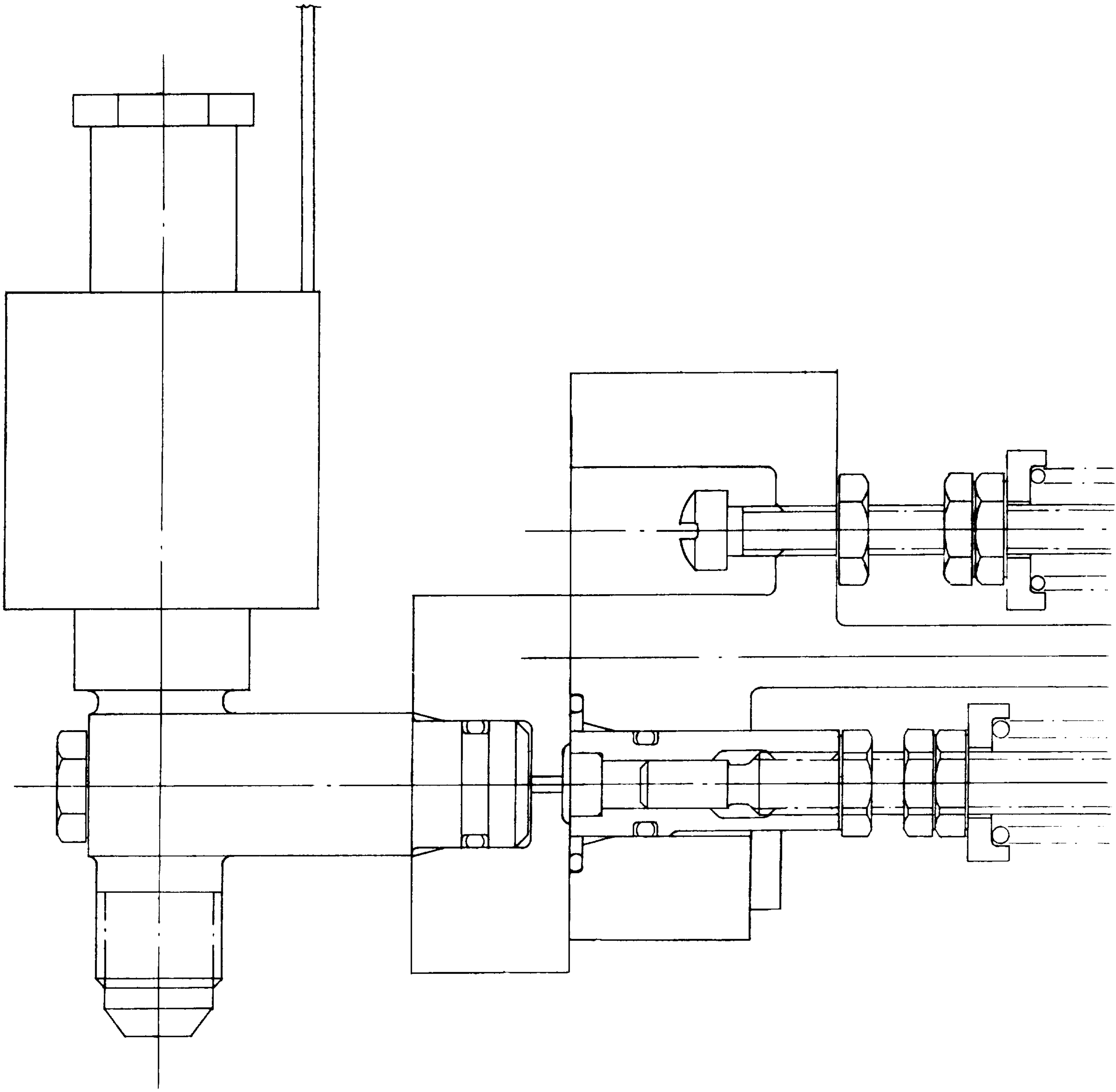
Figure 21



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POSITIVE DISPLACEMENT INJECTOR TEST RIG

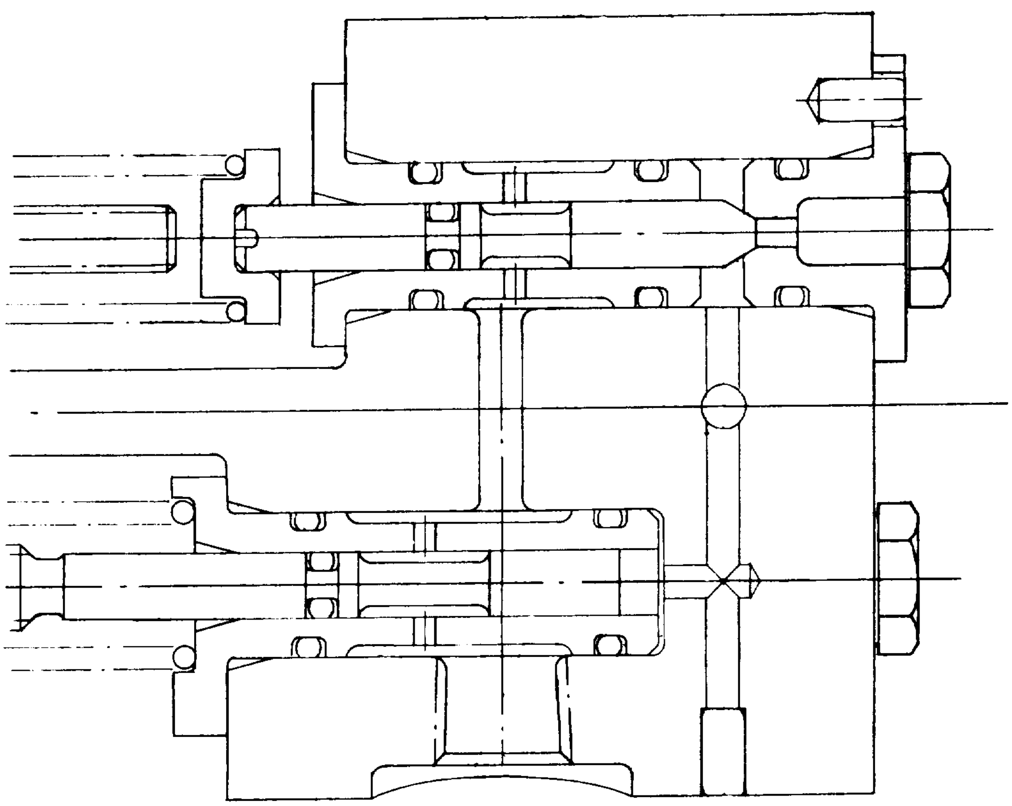

Figure 23

POSITIVE DISPLACEMINT INJECTOR TEST RIG

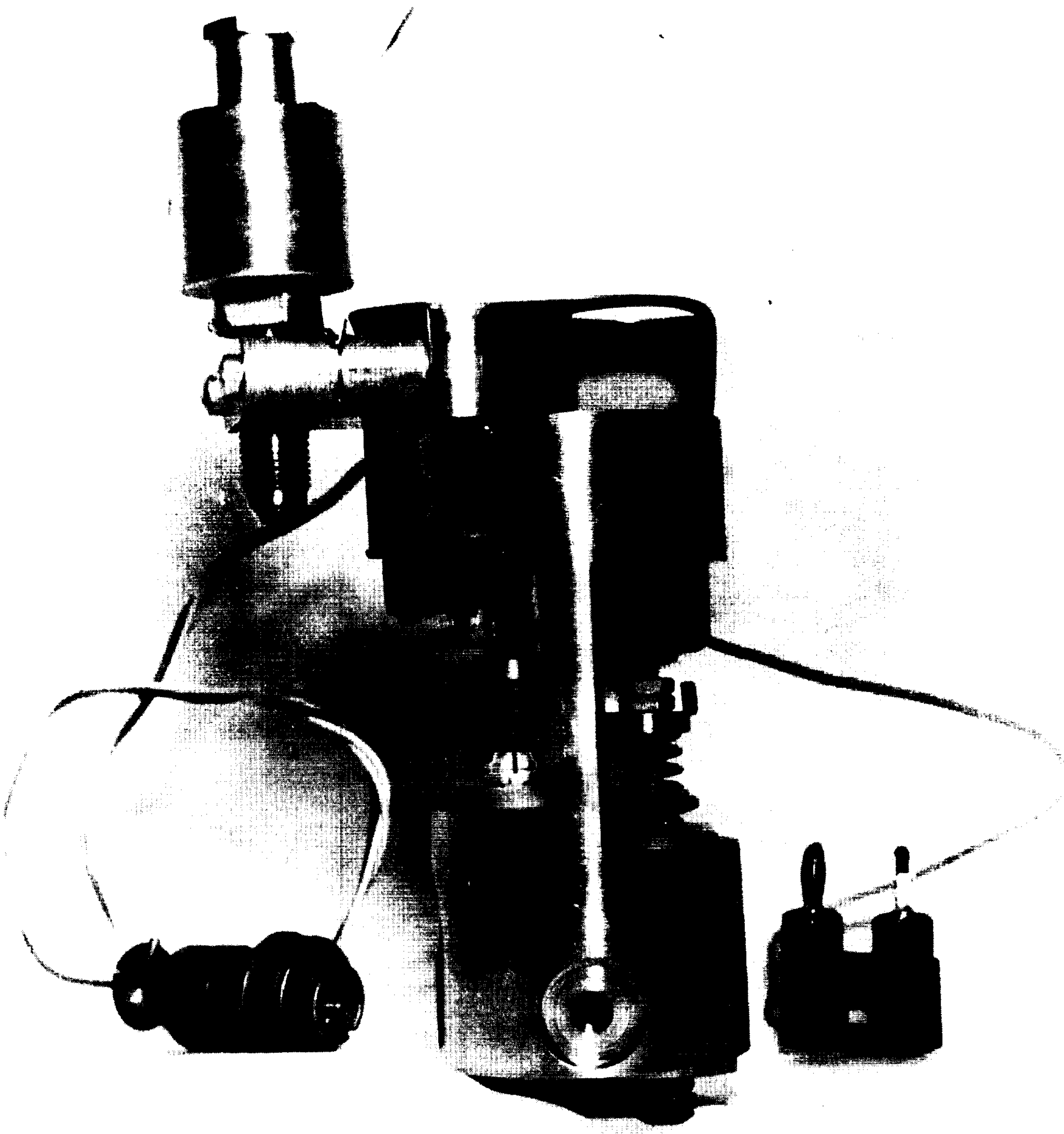

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Figure 24

SCHEMATIC

P.D.I. TEST RIG

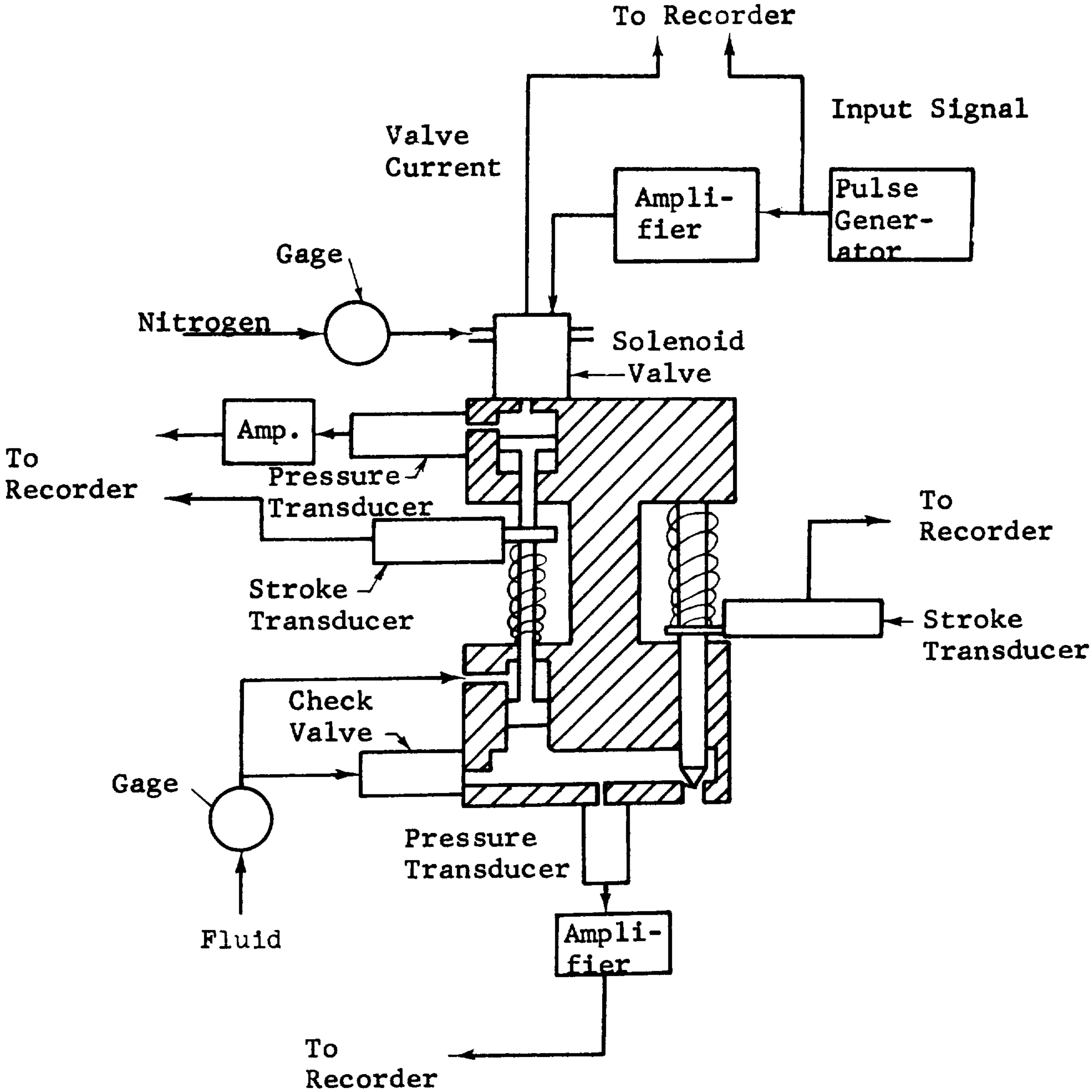

Figure 25

E. Test Program and Results

Tests were conducted to determine the repeatability of pulses and to obtain data on the dynamics of the test rig which could be compared with the computed analysis.

Before conducting these tests the test rig was checked for leakage. None was evident past the dynamic seals either before or after the tests. Leakage past the pintle and propellant piston from the upper to the lower fluid chamber was checked by pressurizing the upper chamber for one minute with fluid at 100 psi. No fluid appeared at the injector orifice during this time. Finally, the leakage at the injector orifice was checked at fluid pressures of 0 to 100 psi. Unfortunately, in this case there was some intermittent leakage, which varied from 0 to 80 drops per minute. The greatest leakage occurred at the higher pressures.

The first test was for pulse repeatability which was determined by comparing the liquid pressure traces of each pulse and by measuring the amount of liquid ejected. Examination of pressure traces, such as Figures 26 and 27, indicated no discernible differences between pulses. Figure 26 is a part of the record of the 2 CPS run. It shows the dynamics of the test rig and it provided a record of the number of pulses in the run. The ejected liquid was weighed on an accurate chemical balance and compared with the calculated weight. The results of this test, shown in Table 9, indicate a maximum deviation of approximately $\pm$ 3.5% with an average at -1.1%. The positive deviation in the first run could have been caused by leakage either before, during or after the run. It would require only four drops of the liquid, which was found to weigh 0.0465 grams per drop, to change the deviation from +3.35% to -1.2%.

The next test was to obtain data on the operation of the test rig. Typical results showing the test rig dynamics and its comparison to the theoretical analysis is shown in Figure 27 and Table 10. There is very good agreement between the test and calculated response for the fill and vent times. Obtaining agreement for the actuation and return times is a little more difficult because of some of the assumptions made in the equations used in the computer program.

For the actuation time the equations assume a constant value for the opposing force, C_3. However, measurements taken from the test traces show that this force varies during the stroke. The reason for this is the variation of the fluid pressures as the pintle movement changes the orifice area, as can be seen in

Figure 27, and there may also be changes in the amount of friction in the system. Computed actuation times for both the high and low measured values of C_3 are shown in Table 10. The test results come close to those for the high values.

F. Test Rig Operating Characteristics

The response of the test rig was relatively slow. The causes of the slow response are the small size of the orifice into the gas chamber and the large amount of friction from the teflon dynamic seals. The test rig orifice was sized to give a minimum actuation time of 0.01 seconds at a spring preload of zero with the nitrogen supply pressure at 300 psi. Increasing the orifice size would of course result in a faster response as has already shown (Figures 7 and 22). The valve used was large enough to permit the rig orifice diameter to be increased by a factor of 4. A flight design would of course use the valve orifice to control flow and would only be large enough to give the desired response. Increasing the preload would cause an increase in both the fill and actuation times (Figure 18). Unfortunately, the teflon seals caused a friction load of approximately 7 pounds which then required a spring preload of 7 pounds in order to overcome this friction on the return stroke. Thus there was in effect an increase of 14 pounds in the preload with the corresponding increase in fill and actuate times. This problem would not exist in any flight design since frictionless bellows seals would be used instead of the teflon O-rings.

TYPICAL TEST TRACE - P.D.I. AT 2 CPS

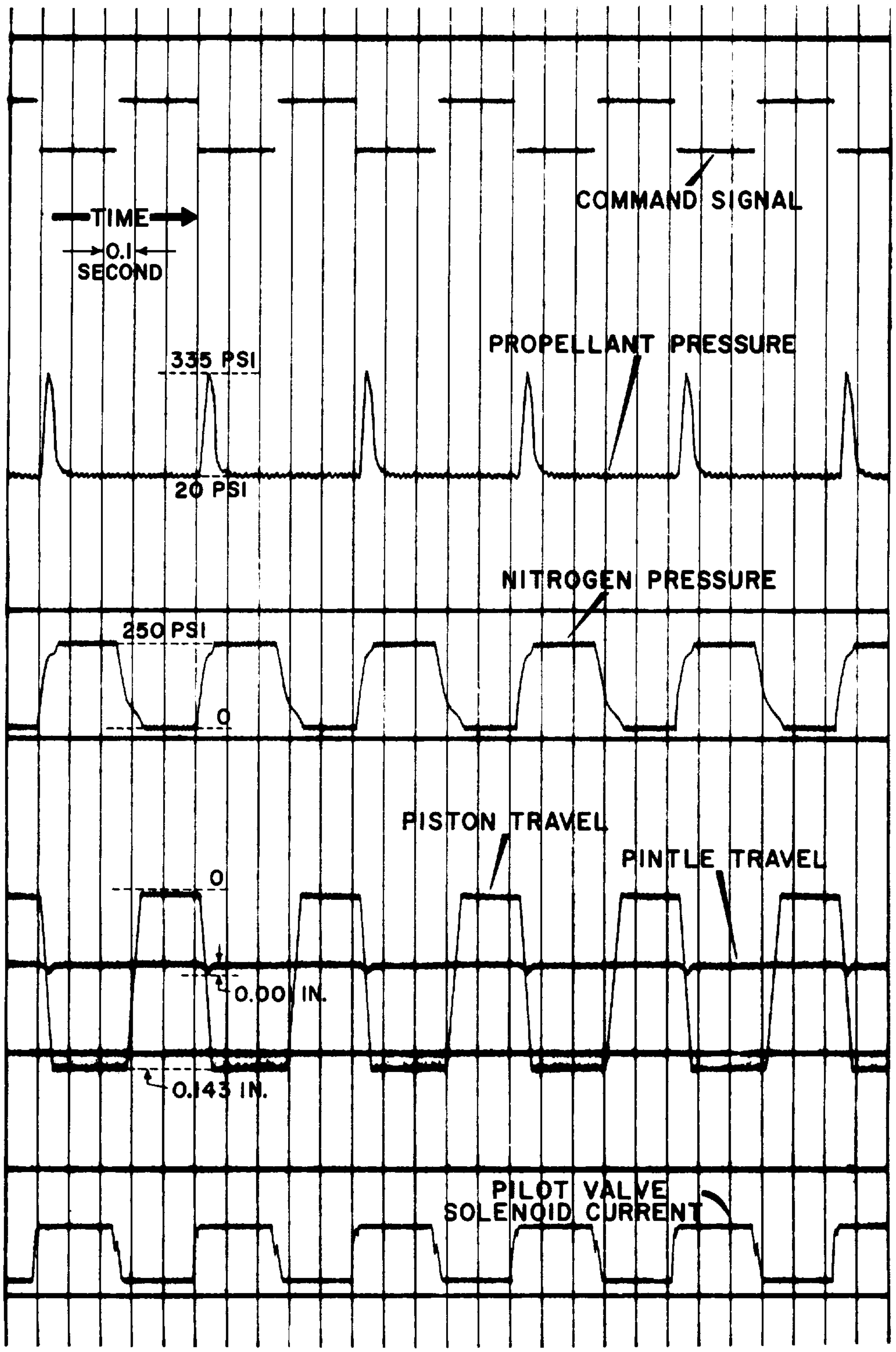

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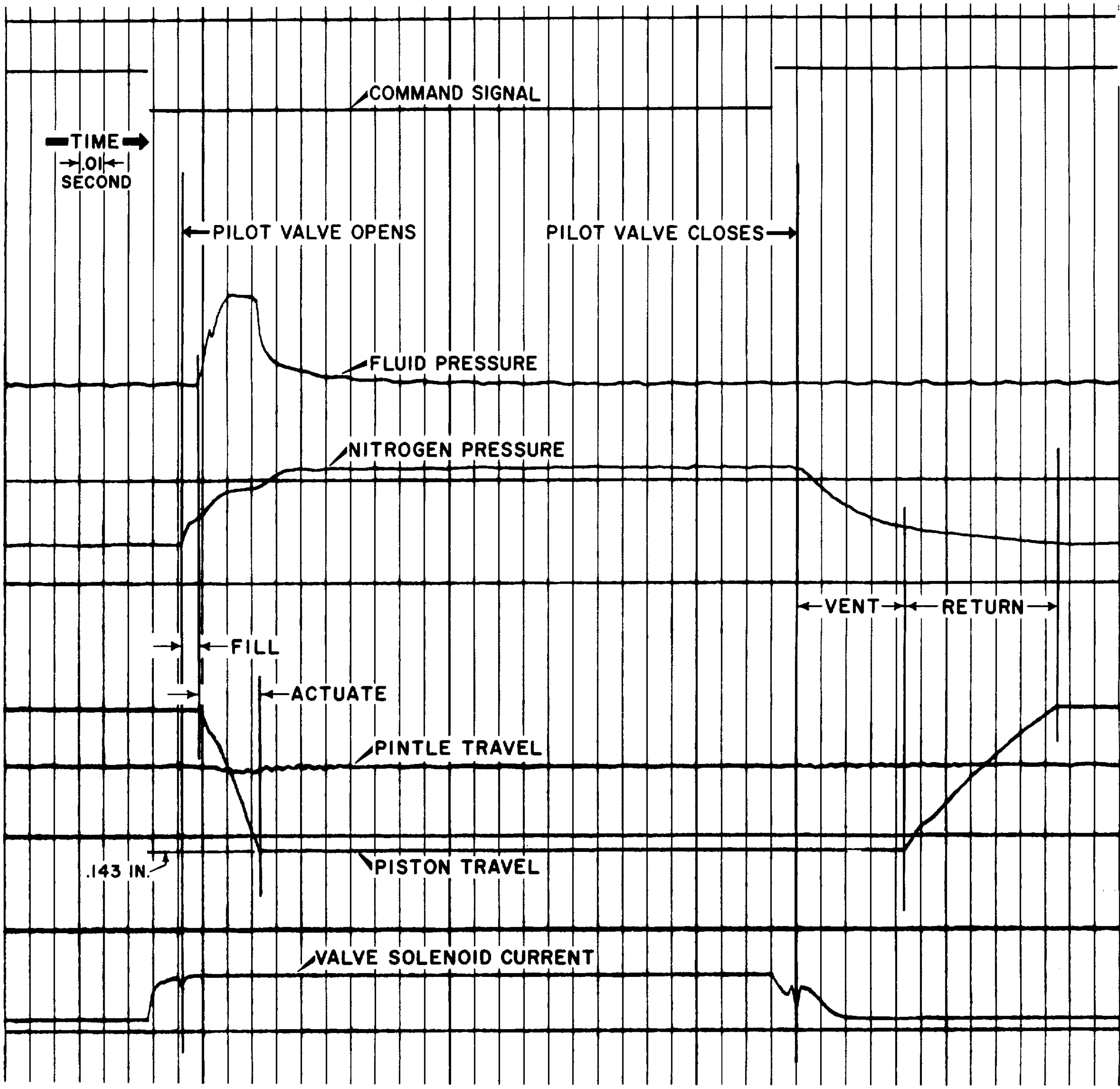
Figure 26


COMMAND SIGNAL
TIME
.01
SECOND
PILOT VALVE OPENS
PILOT VALVE CLOSES
FLUID PRESSURE
NITROGEN PRESSURE
VENT
RETURN
FILL
ACTUATE
PINTLE TRAVEL
.143 IN.
PISTON TRAVEL
VALVE SOLENOID CURRENT

4651

TYPICAL TEST TRACE - P.D.I. AT 2 CPS

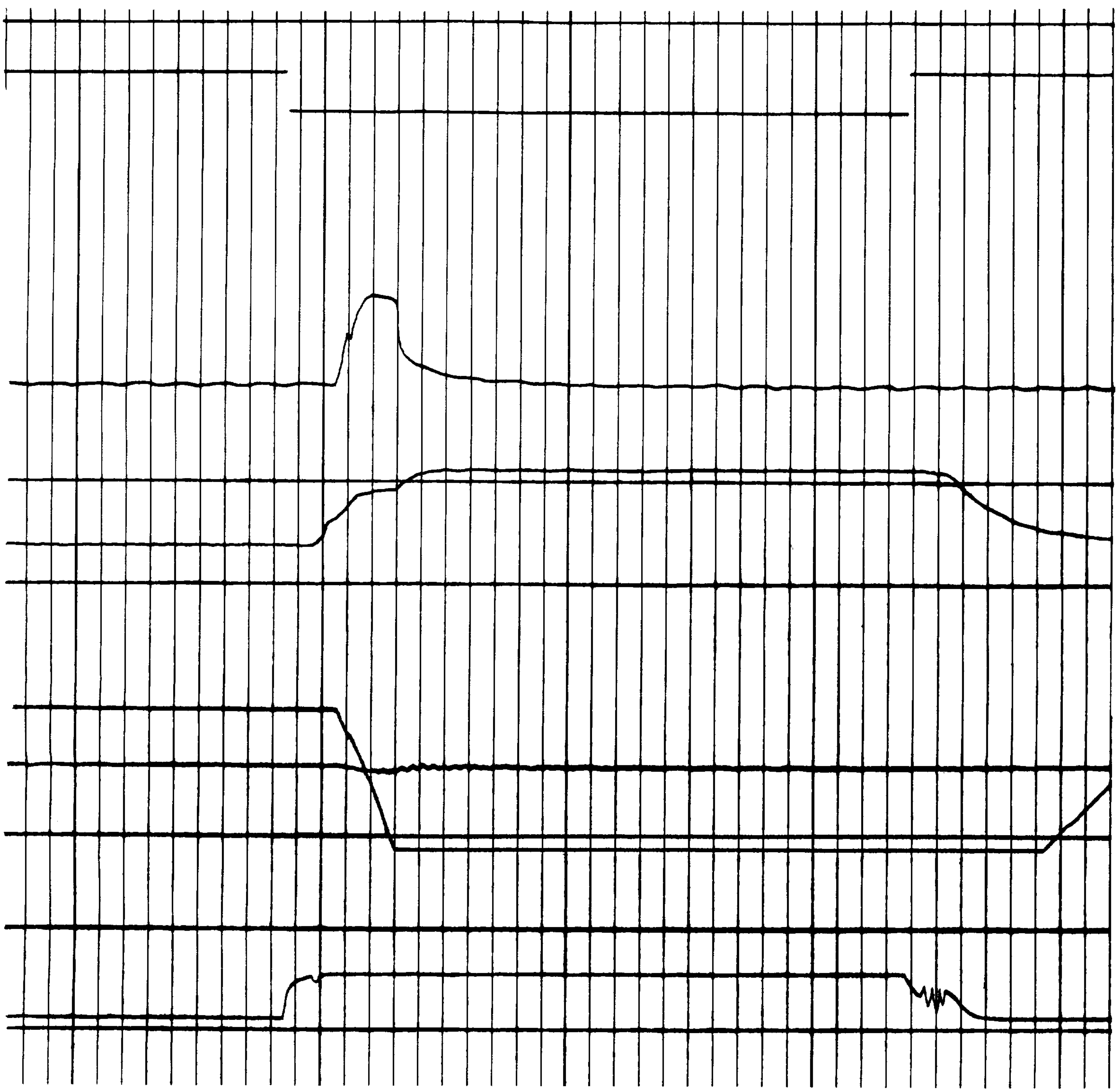


Figure 27

Results of Pulse Repeatability Tests

Run No.	Pulse Frequency cps	No. of Pulses	Wt. of Fluid grams	Wt. of Fluid per Pulse grams	Deviation from Theoretical Weight %
1	2	73	4.2757	.0586	+ 3.35
2	3	73	4.1230	.0564	- .53
3	4	86	4.7930	.0557	- 1.76
4	5	92	5.1194	.0556	- 1.94
5	5	103	5.6208	.0546	- 3.7
6	4	90	5.0129	.0557	- 1.76
7	3	79	4.4683	.0566	- .176

Theoretical weight per stroke = .0567 GM for a .143 in. stroke and fluid specific gravity of .768 @ 70°F.

Nitrogen feed pressure = 300 psi
Fluid feed pressure = 20 psi

Table 9

P.D.I. TEST RIG DYNAMICS

	TEST RIG RESPONSE MILLISECONDS			COMPUTED RESPONSE MILLISECONDS					
RUN NO.	1	2	3	1		2		3	
NITROGEN FEED PRESSURE - PSI.	208	265	400	208		265		400	
				C_3		C_3		C_3	
FILL	11	9	5	16.7	12	16.7	9	16.7	4.95
ACTUATE	50	28.5	17	16.7	40	16.7	18.5	16.7	12.2
				22.7	47.5	26.4	28.5	30.8	19
VENT	30	35	52	29.6		34.9		48.5	
RETURN TO P_2/P_1 = .53	28	29	30	30		30		30	
RETURN	63	64	62	41		41		41	

Table 10

VI PRELIMINARY SYSTEM DESIGN

A typical system design applying the positive displacement injection principle has been investigated. Control system parameters have been established based upon the estimate made in Section III for vehicles operating in essentially a pulsing mode.

A vehicle with a mass of 150,000 lbs. compatible with advanced Saturn capabilities for low earth orbit was selected. Representative of such a mission might be a manned space station for conducting scientific experimentation and serving as a launching platform for deep space probes (Refs. 7 and 8).

A. Specification of Requirements

Based upon the assumed vehicle mass of 150,000 lbs, control system requirements were specified as detailed below:

Gross correction and spin maintenance

Total impulse - 140,000 lb-secs.

Nominal thrust level - 110 lbs.

Nominal impulse bit - 1.1 lb-sec.

Vernier system - low level correction, cyclic disturbances and limit cycle

Total impulse or equivalent - 375,000 lb-secs.

Nominal thrust level or equivalent - 1.1 lbs.

Nominal impulse bit or equivalent - .011 lb-secs.

The gross correction attitude control system has been analyzed applying the high performance Positive Displacement Injection principle. An earth storeable propellant combination (N_2O_4 - 50% UDMH, 50% N_2H_4) was selected for this system. This combination (representative of the earth storeable class) was used in view of temperature conditioned nature of this application, and the probability of its being placed in a near earth orbit. Such considerations detract from the application of the higher energy cryogenic combinations for this particular mission.

A mission more compatible with cryogenic space storage potential represented by a combination such as OF_2 and B_2H_6 would be further enhanced by application of the high performance injector concept. Such an application employing a pulsing mode of operation and requiring a relatively high total impulse capacity would realize a substantial reduction in system weight contrasted to a conventional bipropellant system.

The vernier correction system has investigated application of a reaction wheel system. Such a system was found to be very attractive on a weight basis if used within its limitation of correction for cyclic types of disturbance or limit cycle.

B. Gross Correction Attitude Control System

A preliminary design of a high pressure pulse rocket motor with a positive displacement injector is shown in Figure 28. The design is based on the requirements discussed above.

The thrust chamber is constructed of pyrolytic graphite contained in a stainless steel shell. The pyrolytic graphite is used as a heat sink. Wright Aeronautical Division, Curtiss-Wright Corporation has extensive experience in the design and development of pyrolytic graphite thrust chambers. Test results from other programs and a preliminary heat transfer analysis indicates that the thrust chamber design shown in Figure 28 is feasible for this high pressure pulse application.

The thrust chamber is sized to produce a peak chamber pressure in the order of magnitude of 4000 to 5000 psi. Based on these pressures, maximum thrust is approximately 110 lbs. The exit nozzle is designed to a 200:1 expansion ratio consistent with the discussion in Section IV of this report.

The injector is a gas actuated bellows type PDI similar to that shown schematically in Figure 3. Two poppet type valves are used for opening and closing the oxidizer and fuel injection orifices. These valves are commercially available items. The spring preloads keep the valves closed in the off position. When the system is actuated, increased fuel and oxidizer pressure opens the valves. The injection orifices are sized to give approximately 100 ft. per sec. injection velocity. Impingement injection of fuel and oxidizer is shown to promote better propellant mixing and higher combustion efficiency.

A solenoid valve is used for controlling actuating gas flow. A technique of pulse shaping would be used to increase the response of this valve and therefore the system. The valve opening and closing time is decreased from approximately 0.014 sec to 0.003

sec with this technique.

A bracket type support attaches the solenoid valve to the injector housing. An AN fitting is shown on the drawing in lieu of the solenoid valve. This bracket also forms the housing for the gas piston. The bellows assembly consists of a rod, a cover plate, and the bellows. The bottom end of the rod flares into a flat circular disc. The bellows is welded to the disc end of the rod and to the cover plate. The entire assembly is bolted into the injector housing thru the cover plate. The bellows rod extends thru the cover plate and contacts a rigid bar type support. Contact is made thru a self centering, spherical socket type joint. The gas piston rests on the bar support. Both bellows are preloaded to support the weight of the bellows rods, the bar support, and the gas piston. When the gas piston is actuated it moves the bar support and bellows rods down, synchronously extending both bellows. When the actuating gas pressure is vented, the bellows force, aided by the force created by the partially unbalanced propellant supply pressure, returns the actuating mechanism, positioning it for the next stroke.

Check valves are located at the fuel and oxidizer inlet ports. These valves are also commercially available items. Fuel and oxidizer are fed thru these check valves priming the bellows and poppet valve cavities. Extension of the bellows displaces the predetermined volume of propellant. This increases the propellant pressure forcing the poppet valves open allowing fuel and oxidizer injection into the combustion chamber. The check valves seal the low pressure feed system from the higher pressure developed during the injection stroke.

The injector illustrated provides an impulse bit of approximately 1.1 lb-secs. The maximum pulse frequency for this system is in the order of 10 to 20 cycles per second. The pulse frequency is primarily a function of the tail off portion of the pressure-time transient. The frequency may be increased by decreasing the combustion chamber volume which in turn produces higher peak chamber pressure and possibly higher performance.

Figure 29 shows a schematic representation of the 140,000 lb-sec total impulse PDI system. The propellant expulsion and pressurant gas systems are essentially the same as those for a conventional bi-propellant system.

Nitrogen gas is used to pressurize the propellant tanks and also to actuate the PDI. The gas pressure is reduced from 3000 psi storage pressure to 300 psi for actuation of the injector and

80 psi for the pressurization of the N_2O_4 - 50% UDMH/50% N_2H_4 propellant tanks.

A weight summary of the system is shown on Table 11.

C. Vernier Correction Attitude Control System

The analysis of a reaction wheel system was made to validate the assumption that, for a low torque, cyclic type vernier control requirement, an inertia device would be lighter in weight than a reaction jet device. The primary reason for the anticipated weight saving is that the reaction jet device requires its total energy capability to be carried as propellant and tankage whereas a reaction wheel has the capability of utilizing ambient energy (solar) to provide its required power. Thus, only a power conversion system is required.

The reaction wheel system analysis was performed for a single body axis. Gyroscopic interactions were neglected and constant angular accelerations were assumed. A maximum distributing torque was defined for the vehicle (refer to Specification Requirements) and a response of the reaction wheel system was chosen. With this information the weight of the wheel, motor, and power supply (solar cells) is computed for various values of final angular velocity. It is noted here that the calculated wheel weight is a minimum (with a corresponding large radius); it is more realistic to select a wheel radius and compute a revised weight (for the same moment of inertia). Also the response time used to compute the angular velocity of the wheel is assumed to be a constant for a given case which yields optimistic motor weights for high angular velocities.

The analysis indicates that high reaction wheel angular velocities require excessive motor and power supply weights. Conversely, low angular velocities require large wheel weights for realistic wheel sizes. Further, as the response time increases the wheel weight increases (for a constant wheel radius). On this basis several studies were made to assess total system weight, which was conservatively estimated to be three times the single axis weight. The analysis and computations are presented in Appendix J.

The initial investigation assumed a torque equivalent to 1/2 of a single pulse of the gross correction attitude control engine (110#) located at the vehicle radius (75 ft.). This resulted in unrealistic system weights for reasonable wheel radii (less than 10 feet). Even the modifying assumptions of shorter response time or constant wheel radius, failed to yield reasonable system weights. Thus, the assumption of a similarly located 1.1# thrust engine was made. This resulted in a realistic system. A summary of the characteristics for such a system are shown on Table 11.

Note that the first case was realistically coupled to the larger attitude control engines. It provided controlled torque capability from the minimum generated by the attitude control engines down to zero. Further, the attitude control engines would serve as the desaturation device for the reaction wheel. This precise coupling is not satisfied by the present system.

Under the present assumptions another system would be required to provide the coupling. 1.1 lb. thrust level engines could be used. This would increase the weight of the vernier system both by the addition of components and propellant. However, the reaction wheel approach for the vernier requirement still appears dictated. If a mass expulsion system were to provide the entire capacity of this system, propellant weight alone would be the order of 1400 pounds. The additional weight required for coupling and wheel desaturation would not be expected to be sufficiently high as to preclude use of the reaction wheel system.

PULSE ROCKET MOTOR

(1.0 Lb Sec Per Pulse)

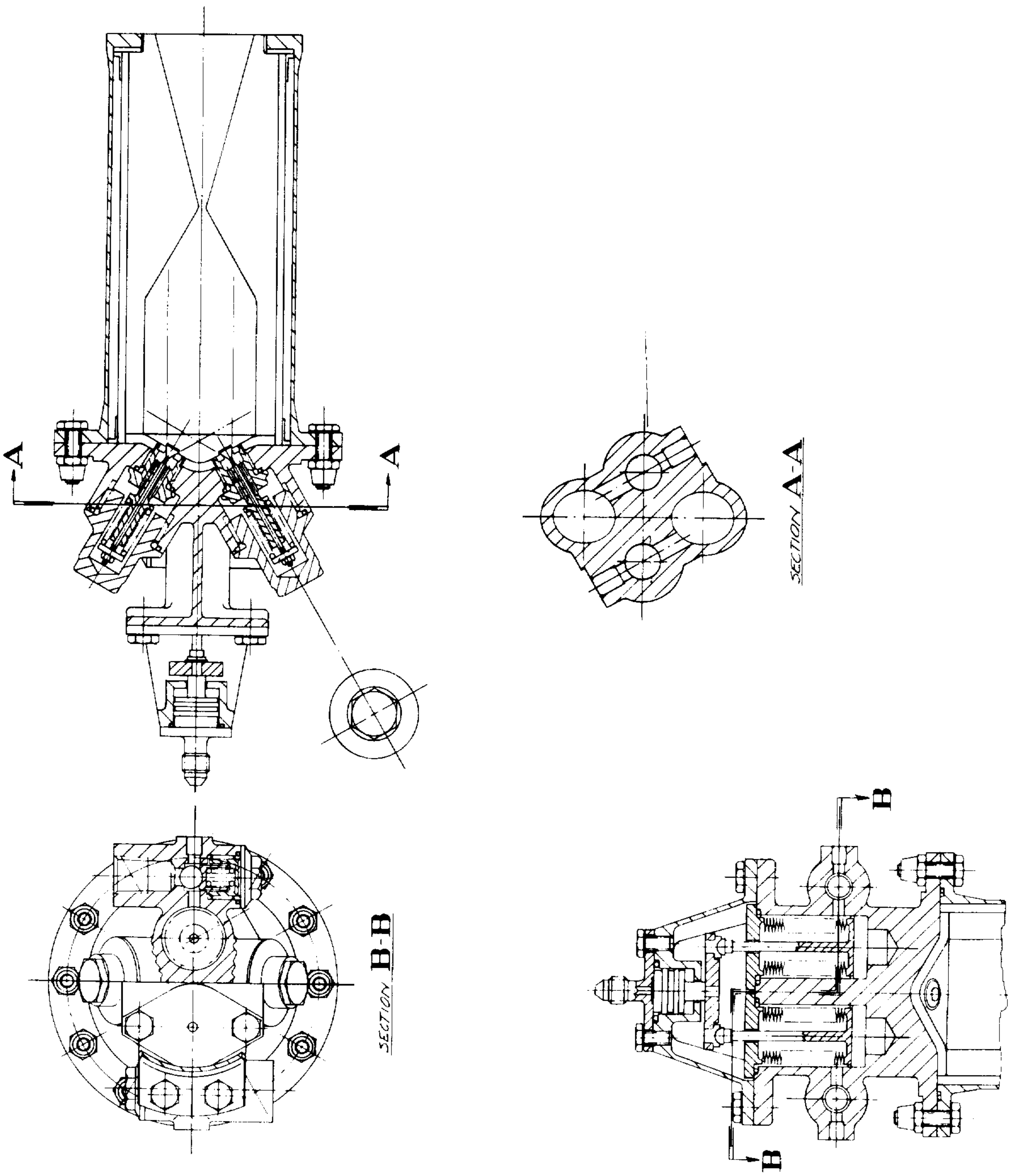


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Figure 28

PDI SYSTEM SCHEMATIC

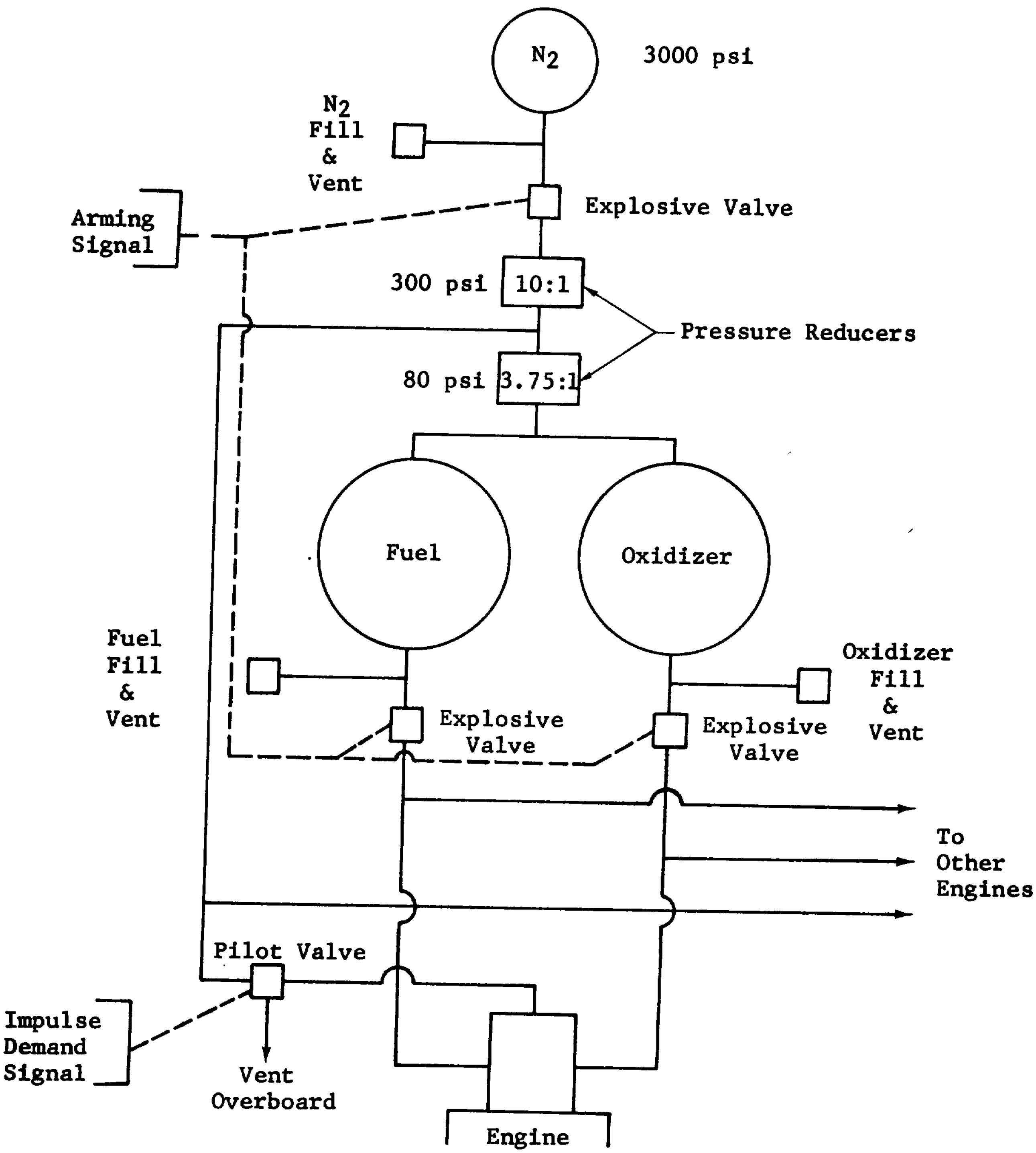

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Figure 29

Typical System Weight Estimate
Gross Correction System
Positive Displacement Injection
High Pressure
N_2O_4 - 50% UDMH/50% N_2H_4

<u>Description</u>

Impulse bit, lb-sec.	1.1
Thrust, lbs.	110
Total impulse, lb-sec.	140,000
Expansion ratio	200
Peak chamber pressure, psi	4000
Tank pressure, psi	80
80% Theoretical Isp, sec.	270

<u>Weight, Lbs.</u>

8 Thrust chambers	12.0
8 Injectors	16.9
Propellant tanks	7.8
Expulsion bladders	2.7
Propellant	518.0
Gas + gas tank	26.3
Lines	2.5
Controls	1.0
Total	587.2

Vernier Correction System
Reaction Wheel

<u>Description</u>

Equivalent impulse bit, lb-sec.	.011
Equivalent thrust, lbs.	1.1
Equivalent total impulse, lb-sec.	375,000

<u>Characteristics</u>

Wheel radius, feet	1.0
Response, secs.	0.010
Single axis weight, lbs.	72
Total system weight, lbs.	216*

* Would be heavier considering requirement to provide coupling with gross correction system.

Table 11

VII PROGRAM FOR THE PERFORMANCE DEMONSTRATION OF THE POSITIVE DISPLACEMENT INJECTOR PRE-INJECTION PRINCIPLE

A. Introduction

In view of the potential capability of improving propellant performance of a pulse engine using the positive displacement injector, a program for test evaluation of the operating principle is suggested. This section summarizes the operating technique considered in Section IV and then outlines a test demonstration approach.

B. Summary Discussion

It has been concluded that weight reduction of an attitude control system for high total impulse requirements depends primarily on propellant performance improvement and only to a minor degree on inert system weight optimization. The study has indicated that the injector is capable of using a modified technique which will permit pulse operation at elevated chamber pressure with consequent capability of using high nozzle expansion ratios within a reduced envelope. A higher theoretical specific impulse results from both the higher operating chamber pressure and increased nozzle expansion ratio and thus a reduced propellant requirement. The magnitude of the improvement will vary dependent upon the propellants considered but will be in the order of 8%.

The technique utilized would be to inject propellant into the combustion chamber at a very rapid rate consistent with the injector's capability but not feasible in a system using conventional valving. Propellant injection would be accomplished within the ignition delay time and thus would be completed against essentially no chamber back pressure. The injected propellant would combust in a chamber of reduced volume with consequent generation of high chamber pressure.

In addition to the theoretical improvement in performance, a further gain considering combustion efficiency appears possible. The reduced chamber volume and throat area suggest an increase in C* efficiency; confinement of the propellant in a reduced volume should promote better mixing and increase the precent of propellant totally combusted, and the effect of the reduced nozzle throat diameter should be to reduce the mass of propellant escaping from the chamber uncombusted prior to ignition. Coupled with improved performance by virtue of the increased chamber pressure and high expansion ratio, a significant decrease in propellant supply could result.

C. Suggested Program and Objectives

The potential of this technique suggests a program for the performance demonstration of the positive displacement injector pre-injection principle. The program would be designed to demonstrate the feasibility of the operating technique in improving propellant performance and to provide the basis for a flight weight engine design.

It would consist of three phases as outlined below:

a. Initial bench tests and combustion analysis.

b. Engine development and performance testing to optimize the design and demonstrate the operating principle.

c. Demonstration of the operating capabilities of a flight type design.

Phase 1

Under this phase of the program, the propellant combination selected would be investigated both analytically and by means of bench type calorimeter tests. Ignition delay time as a function of oxidizer vapor pressure and fuel injection rate would be determined. Test results coupled with the theoretical analysis would be used to establish initial design criteria for the injector and combustion chamber.

Phase 2

Based upon the results of this initial analysis, a heavy duty chamber and injector would be designed and hardware fabricated. The design of this unit would be such that variation of physical dimensions is possible. For instance, it would permit variation in chamber volume, length and throat diameter. Provision would also be made for varying propellant injection velocities and oxidizer-fuel time sequencing. A test program would be conducted to determine the chamber configuration and injector characteristics for optimum performance. The results would be evaluated and compared to predicted performance for a conventional engine of comparable impulse bit capability.

It is suggested that an engine with a nominal impulse bit of 1.0 pound-seconds be used. This size impulse bit appears to be fairly representative of anticipated requirements.

The test program would consist of running various engine configurations measuring impulse per pulse and propellant consumption per pulse. Initial tests arriving at an optimized configuration would be conducted exhausting to sea level back pressure. The testing would then be repeated exhausting to simulated altitude conditions for the more promising configurations. Temperature measurements to be used in support of the flight type design program would be made in addition to recording the chamber pressure-time and thrust-time relationships.

Phase 3

The third phase of this program would be the generation of the design of a pyrolitic graphite chamber and nozzle. It would also include fabrication and test of such a chamber using the configuration optimized under Phase 2.

This chamber would be used to demonstrate operating capability in terms of erosion resistance, performance based on both single and repeated pulsing and resistance to "heat soak" under various duty cycles. Tests would be conducted exhausting to both sea level ambient pressure and simulated altitude.

Successful demonstration of improved performance using the pre-injection operating technique and demonstrated operational capability of the pyrolitic graphite would provide a pulse engine design applicable to missions basically requiring pulse operation.

D. Propellant Considerations

Attitude control system propellant weight requirement can be reduced by both improving propellant performance or by using higher energy propellants. The positive displacement injector indicates capability of improved performance by using the pre-injection technique, and its design also appears adaptable to a wide variety of propellant combinations.

For the test demonstration program outlined herein, a propellant selection is required. Materials and operating parameters would be different for various combinations. The optimum propellant choice would appear restricted to either the earth storeable or space storeable, mild cryogenic combinations. Applicability of the deep cryogenics for a pulsing attitude control system does not seem likely.

The more immediate application for such a device would appear to favor an earth storeable combination such as nitrogen tetroxide and UDMH. At this time, a pulsing mission of high total impulse requirement compatible with space storeable cryogenics has not been identified. However, future missions compatible with a propellant combination such as diborane and oxygen difluoride might well develop. Considering the relative advantages of either approach, the B_2H_6-OF_2 propellant combination appears desirable in view of the following:

a. The additional performance gain represented by this high energy combination compared to earth storeables.

b. Its particular applicability to the high performance PDI operating technique. This combination indicated the largest increase in theoretical performance operating at elevated chamber pressures of the combinations investigated.

c. Development of an engine for this propellant combination should reduce additional development required for its application to an earth storeable combination. On the other hand, development of the engine for an earth storeable combination might well not be as applicable to a higher energy combination.

d. For some applications, the performance increase indicated for the injector coupled with the adaptability to the high energy propellants might well overcome the limitation represented by its basic restriction to a pulsing mode. Performance degradation associated with such operation would not be particularly detrimental if more than counterbalanced by demonstrated suitability to the high energy propellants.

e. Such a program would contribute to the advancement of the "state of the art" of high energy propellants.

The earth storeable combination (N_2O_4 - UDMH) would be favored considering:

a. This combination appears to present more immediate application potential.

b. Development of the injector for this combination would allow application of a more advanced technology. Thus, a reduced development effort would probably be required.

A consideration of the above would tend to favor application of the high energy combination. It is thus recommended that test demonstration of the injector operating principle be accomplished using the diborane, oxygen difluoride propellant combination.

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7. A Report on the Research and Technological Problems of Manned Rotating Spacecraft, National Aeronautics and Space Administration, Langley Research Center, Langley Station, Va., NASA TN D-1504, August 1962.

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APPENDIX A

CONTROL SYSTEM REQUIREMENTS COMPILATION

The results of an industry and government agency survey with regard to attitude control system requirements is contained in Tables A.1 thru A.8. Information obtained thru the survey was further supplemented with data from such other sources as technical journals and reports.

It is to be expected that changes have been made in some programs which are not reflected in this compilation. Thus it undoubtedly does not represent present requirements in all cases.

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP I

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Communication satellite 24 hour orbit	Syncom II	Dev.	5 yr	28VDC	-	0 to 100	N_2O_4 and MMH	In orbit	Synchronization and erection	605	6000	Pitch Yaw	2	5	0.4	1500	2.1	-
									Station keeping		19000	Pitch Yaw	2	5	0.4	0.65	2.1	1.25
Communication satellite 24 hour orbit	Syncom I	Dev.	1 yr	28VDC	28	30 to 110	N_2	In orbit	Orientation and velocity	70	155	Axial and lateral	2	.01	-	-	-	-
							90% H_2O_2		Orientation and velocity		754	Jets	2	1-2.5	-	-	-	-
Surveillance satellite	-	Study	Mos	28VDC	-	-65 to 135	-	In orbit	Station keeping	3000	10000	-	1	100-500	400	400	Every 3 mos	Every 3 mos.
								Injection	Injection Corrections		20000	-	1	1000-5000	N.A.	N.A.	N.A.	N.A.
								In orbit	Perturbations		100,000	-	1	100	3000	3000	Every 2 mos	Every 2 mos.
Lunar orbiter	-	Study	Mos	28VDC	-	-200 to 200	-	Orbit	Attitude control	Few hundred	50-100	Pitch	2	.01	.002	-	.01	-
Weather satellite	Tiros	Oper	6 mos.	28VDC	-	-65 to 135	Solid	Orbit	Spin control	270	14	Yaw	10	5	1.5	N.A.	N.A.	N.A.
Synchronous satellite	-	Proposal	3 yrs.	28VDC	-	-100 to 165	-	Injection	Injection error	500	600	-	1	1-10	N.A.	600	N.A.	N.A.
								Orbit	Longitudinal drift		200	-	1	1-10	N.A.	90	N.A.	-
								Orbit	Inclination		9000	-	1	10-100	N.A.	3000	N.A.	-
								Orbit	Nodal rotation		1400	-	1	1-10	N.A.	-	N.A.	-

Table A.1

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP I

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Earth orbiting satellite for astronomical observation	O.A.O.	Dev.	1 yr	-	-	-	N_2	In orbit	Initial stabilization and solar pointing	3500	288? (1440)	-	12	0.1	-	-	-	-
								In orbit	Dumping fine reaction wheels		2592? (480)		6	.0021	-	-	-	-
Earth orbiting satellite	O.G.O.	Dev.	1 yr	-	-	-	Argon	In orbit	Initial orientation and wheel dumping	1000-1500	700 (P060) 275 (E60)	-	6	.05	-	-	-	-
Weather satellite	Nimbus	Dev.	6 mos.	-	-	-	N_2	In orbit	Initial orientation and wheel dumping	-	330	Pitch Yaw Roll	2 2 2	.062 .089 .090	- - -	- - -	- - -	- - -
Orbiting satellite	O.S.O.	Dev.	6 mos.	-	-	-	N_2	In orbit	Spin up and de-spin	440	290		2	0.1	-	-	-	-
									Pitch precession of spin axis		290		2	.05	-	-	-	-
Injection stage for satellite vehicle	Agena	Oper.	2 yrs.	28VDC	12	-8 to 100	UDMH, 89.3% N_2O_4 and 10.7% NO	In orbit	Station keeping and attitude control	5300	1400-7700	Pitch Yaw Roll	2 2 2	10 10 10	.15 .15 .15	- - -	10 10 10	- - -
											17300-23600	Pitch Yaw Roll	2 2 2	.5 .5 .5	.0075 .0075 .0075	- - -	3 3 3	- - -
								In orbit	Orbit velocity control	-	45,000		2	20	10	3000	.2	.00074

Table A.2

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP I

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Manned rotating spacecraft 300 nautical mile earth orbit	-	Circa 1970	1-5 yrs.	-	-	-	-	In orbit	Attitude control Station Keeping	171000	400,000/yr 115,000/yr	-	12	50	-	-	-	-
Manned rotating spacecraft 250 nautical mile orbit	-	Circa 1970	1-5 yrs.	-	-	-	-	In orbit	Attitude Control Station Keeping	171000	400,000/yr 440,000/yr	-	12	50	-	-	-	-
24 hour satellite	-	Study	2 yrs.	-	-	-	-	In orbit	Orbit Correction	800	1600-12000	-	-	.32-10	-	-	-	-
									Station Keeping		480-2600	-	-	.2-8	-	-	-	-
									Attitude Control		1140	-	-	.01-.1	-	-	-	-
24 Hr. satellite	-	Study	2 yrs.	-	-	-	-	In orbit	Orbit Correction	6000	12000-90000	-	-	2.5-75	-	-	-	-
									Station Keeping		3600-19500	-	-	1-50	-	-	-	-
									Attitude Control		15600	-	-	.1-1.0	-	-	-	-
24 Hr. satellite	-	Study	2 yrs.	-	-	-	-	In orbit	Orbit Correction	28000	56000-420000	-	-	11-350	-	-	-	-
									Station Keeping		16800-91000	-	-	5-300	-	-	-	-
									Attitude Control		84400	-	-	1-10	-	-	-	-

Table A.3

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP II

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Unmanned lunar soft landing	Surveyor	Dev.	70 hr.	22-29V	2.5	-50 to 100	N_2	Coast	Attitude Control	2500	300	All	3	.06	.0015	Cont.	50	-
			60 sec.		3.0		MMH, N_2O_4 and NO	Midcourse	Attitude Control during trajectory correcting maneuver		5000	Pitch and Yaw	3	30-105	-	Cont.	-	-
			4 min.				MMH, N_2O_4 and NO	Landing	Attitude control during descent phase		44000	Pitch and Yaw	3	30-105	-	Cont.	-	-
Manned lunar landing		Dev.	2 hr.	28VDC	56	-	N_2O_4, 50% N_2H_4 and 50% UDMH	Separation Deorbit	Translation and maneuver Partial Attitude Control	-	7000	Pitch Yaw Roll	4 4 4	15 15 15	.15 .15 .15	500 500 500	- - -	- - -
								Coast	Attitude Control		100							
								Retro	Maneuver and partial attitude control		2250							
								Land	Partial attitude control		5470							
								Launch	Partial attitude Control		900							
								Coast	Maneuver and attitude control									
								Rendezvous	Maneuver, translate, att. cont.		9000							

Table A.4

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP II

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Manned lunar landing and return to orbit	Apollo lunar excursion module	-	4 hr	28VDC	-	30 to 110	N_2O_4, 50% N_2O_4 and 50% UDMH	Lunar landing and return to orbit	Attitude and translational control	20,000 initial	42,000	-	16	60	.3	4.1	.1	4
Planetary spacecraft	Mariner	Oper.	1 yr	Solar panels and battery 28VDC	-	50 to 110	N_2	Acquisition Cruise Midcourse and Terminal Control	Spacecraft Orientation	450	260	Pitch Roll Yaw	10	.01	2x 10^{-4}	2.4	Every 2000 secs.	-
Lunar spacecraft	Ranger	Oper.	50 days	Solar panels and battery 28VDC	-	50-110	N_2	Acquisition Cruise Midcourse and Terminal Control	Spacecraft Orientation	675	200	Pitch Roll Yaw	10	.017	12x 10^{-4}	2.4	Every 500 secs.	-
Instrumented probe from Earth to within 0.1 A.U. of the Sun	Solar Probe	Study	1 yr.	-	-	90 to 150	Cold gas or condensable vapor	Post injection	Attitude Control	300 to 400	500-1000	3 Axes	6	10^{-3} to 10^{-4}	10^{-3}	N.A.	N.A.	N.A.
Manned orbiting skip glide reentry vehicle	Dyna-Soar	Dev.	Partial orbit	28VDC	24	Propellant tank environment 25-140	90% H_2O_2 was LH_2 and LO_2	Exit	Attitude Control	10,000-15,000	5480	Pitch	4*	42	4.2	210	-	-
								Orbit	Attitude Control		1960	Yaw	4*	34	3.4	170	-	-
								Reentry	Attitude Control		9660	Roll	4*	19	1.9	95	-	-

*two redundant systems; 6 motors per system

Table A.5

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP II

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Earth orbiting vehicle (1 man)	Mercury	Oper.	1-18 orbits	28VDC	28	-	90% H_2O_2	In orbit and Reentry	Attitude Control	2500	4000	Pitch	2	24	-	-	-	-
													2	1	-	-	-	-
												Yaw	2	24	-	-	-	-
													2	1	-	-	-	-
												Roll	2	6	-	-	-	-
													2	1	-	-	-	-
											4000	Pitch	2	0-24	-	-	-	-
												Yaw	2	0-24	-	-	-	-
												Roll	2	0-6	-	-	-	-
Earth orbiting vehicle (2 man). Space rendezvous capability	Gemini	Dev.	2 wks.	28VDC	.15 watt-hrs per pound of prop's.	25 to 140	N_2O_4, 50% N_2H_4 and 50% UDMH	-	Attitude Control	-	20,000	Pitch	2	50	.2	Cont.	1	-
												Yaw	2	50	.2	Cont.	1	-
												Roll	4	25	.1	Cont.	1	-
									Orbital Correction and Maneuvering	-	180,000	-	-	-	-	-	-	-
Lunar landing and return (3 man)	Apollo Command Module	Dev.	2 wks.	18.5-30.5 VDC	-	35 to 160	N_2O_4, 50% N_2H_4 and 50% UDMH	-	Attitude Control during Propelled and Coast Regimes	-	48,000	Pitch	2	100	2	Cont.	-	-
												Yaw	2	100	2	Cont.	-	-
												Roll	4	100	2	Cont.	-	-
Lunar landing and return	Apollo Service Module	Dev.	2 wks.	18.5-30.5 VDC	.15 watt-hrs. per pound of prop's.	-65 to 165	N_2O_4, 50% N_2H_4 and 50% UDMH	-	-	-	300,000	Pitch	4	100	2	5000	-	-
												Yaw	4	100	2	5000	-	-
												Roll	8	100	2	5000	-	-

Table A.6

CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP II

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Second stage of four stage solid propellant research rocket	Scout	Oper.	1 min.	28VDC	28	40-160	90% H_2O_2	Boost	Attitude Control	13,000-5500	26,000	Pitch	2	510	50	Cont	2	-
												Yaw	2	510	50	Cont	2	-
												Roll	4	40	4	Cont	2	-
Third stage of four stage solid propellant research rocket	Scout	Oper.	1-30 mins	28VDC	28	40-160	90% H_2O_2	Boost	Attitude Control	3400-1300	1600	Pitch	2	44	4	Cont	-	-
												Yaw	2	44	4	Cont	-	-
												Roll	4	14	1.4	Cont	-	-
								Coast	Attitude Control	1300	1000	Pitch	2	2	.2	Cont	-	-
												Yaw	4	3	.3	Cont	-	-
												Roll	4	3	.3	Cont	-	-
Fourth stage of four stage solid propellant research rocket	Scout	Study	1-30 mins.	28VDC	28	-	-	Boost	Attitude Control	600-80	350	Pitch	2	10	-	-	-	-
												Yaw	2	10	-	-	-	-
												Roll	2	10	-	-	-	-
								Coast	Attitude Control	80	-	Pitch	2	.1	-	-	-	-
												Yaw	2	.1	-	-	-	-
												Roll	2	.1	-	-	-	-
Skip glide mission test vehicle	Asset	Dev.	-	28VDC	28	30-190	90% H_2O_2	Exit, Orbit and Reentry	Attitude Control	-	6000	-	-	40	-	-	-	-
												-	-	15-5	-	-	-	-
												-	-	2	-	-	-	-

Table A.7

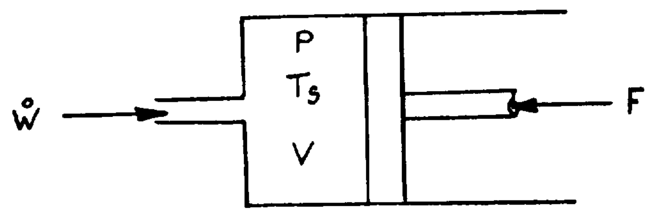
CONTROL SYSTEM REQUIREMENTS COMPILATION GROUP II

Mission description	Program designation	Program status	Mission duration	Electrical power source	Maximum power available per motor (watts)	Operating temperature range (°F)	Propellant selection	Mission phase	Control required for	Approx. vehicle mass (lbs.)	Total impulse (lb-secs)	Axis	Number of motors	Thrust level (lbs)	Desired minimum impulse bit (lb-secs)	Maximum impulse bit required (lb-secs)	Maximum pulse repetition rate at minimum impulse bit (pulse/sec)	Maximum pulse repetition rate at maximum impulse bit (pulse/sec)
Test vehicle for pre-flight rating of Apollo capsules	Little Joe II	Dev.	Mins	28VDC	28	-	90% H_2O_2	-	Attitude Control	-	20,000	Pitch	2	500	-	Cont.	-	-
												Yaw	2	500	-	Cont.	-	-
												Roll	4	40	-	Cont.	-	-
Upper stage of boost vehicle	Centaur	Dev.	-	28VDC	-	-	90% H_2O_2	-	Stage Engine Propellant Bottoming and Attitude Control	32,000	20,000	-	4	50	-	Cont.	-	-
													2	3	-	Cont.	-	-
													4	1.5	-	Cont.	-	-
Rendezvous of C-5 payload in Earth orbit	-	Study	10 days	N.A.	N.A.	-	N_2O_4, 50% N_2H_4 and 50% UDMH	Rendezvous	Attitude Control	240000	410,000	Pitch	2	250	30	2100	0.20	The order of seconds or minutes.
												Yaw	2	250	30	2100	0.20	
												Roll	4	250	65	3500	0.01	
									Docking	220000	210,000	-	6	1000	1000	Steady State	0.1	0.1

Table A.8

APPENDIX B

DYNAMICS OF THE PNEUMATIC ACTUATOR PISTON



The mass flow of gas into the cylinder is given by:

$$\mathring{W} = \frac{C_2 C_D P_s a}{\sqrt{T_s}} f_1\left(\frac{P}{P_s}\right) \qquad (1)$$

where $f_1\left(\frac{P}{P_s}\right) = \frac{C_1}{C_2}\left(\frac{P}{P_s}\right)^{\frac{1}{K}}\sqrt{1-\left(\frac{P}{P_s}\right)^{\frac{K-1}{K}}}$

The volumetric flow is given by:

$$Q = \frac{\mathring{W}}{\rho} = \frac{12 R T_s \mathring{W}}{P}$$

$$\therefore\ Q = 12 C_2 C_D R a \sqrt{T_s}\ \frac{P_s}{P}\ f_1\left(\frac{P}{P_s}\right) \qquad (2)$$

The energy equation is

$$\mathring{W} c_p T_s = P \frac{dV}{dt} + \frac{d}{dt}\left(\rho V c_v T_s\right) \qquad (3)$$

By substitution of perfect gas relationships, this can be reduced to

$$\frac{dP}{dt} + \frac{KP}{V}\left(\frac{dV}{dt} - Q\right) = 0 \tag{4}$$

$$V = A(Z_0 + Z) \quad \text{AND} \quad P = \frac{F}{A} \quad \therefore \quad \frac{dV}{dt} = A\frac{dZ}{dt} \quad \text{AND} \quad \frac{dP}{dt} = \frac{dF}{A\,dt}$$

Equation (4) can be rewritten as

$$\frac{dF}{dt} + \frac{KF}{A(Z_0+Z)}\left(A\frac{dZ}{dt} - Q\right) = 0 \tag{5}$$

By substituting (2) in (5) the equation for the motion of the piston becomes

$$\frac{dF}{dt} + \frac{KF}{A(Z_0+Z)}\left[A\frac{dZ}{dt} - 12\,C_2 C_D R a\sqrt{T_s}\,\frac{P_s}{P} f_1\left(\frac{P}{P_s}\right)\right] = 0 \tag{6}$$

Equation (6) is of the complex non-linear type and has been programme for an I.B.M. 704 digital computor, as have equations (9) and (10).

The mass flow rate of the gas out of the cylinder is given by

$$\mathring{W} = \frac{C_2 C_D P a}{\sqrt{T_s}} \tag{7}$$

The energy equation is

$$P\frac{dV}{dt} + \frac{d}{dt}\left(\rho V C_v T_s\right) + \mathring{W} C_p T_s = 0 \tag{8}$$

By again making the proper substitutions this becomes

$$\frac{dF}{dt} + \frac{KF}{A(Z_0+Z)}\left[A\frac{dZ}{dt} + 12\,C_2 C_D R a\sqrt{T_s}\right] = 0 \tag{9}$$

When the volume above the piston is being filled to a pressure sufficient to overcome the force "F" the equation is

$$\frac{dP}{dt} - \frac{K}{A Z_o} 12 C_2 C_D R a \sqrt{T_s} \; P_s \, f_1\left(\frac{P}{P_s}\right) = 0 \tag{10}$$

The time for the pressure to decay to F/A is given by

$$t = \frac{A(Z_o + Z)}{C_D a \sqrt{K g R T_s}} \left(\frac{2}{K-1}\right) \sqrt{\left(\frac{K+1}{2}\right)^{\frac{K+1}{K-1}}} \left[\left(\frac{P_1}{P_2}\right)^{\frac{K-1}{2K}} - 1\right] \tag{11}$$

WHERE : $P_1 = P_S$

$P_2 = \frac{F}{A} = \frac{C_{32} + C_4 Z}{A}$

C_4 = spring rate

C_{32} = effective constant force in the direction of the return stroke.

= preload + propellant pressure x area - friction + ...etc.

In equations (6) and (9)

$F = C_3 + C_4 Z$

where C_3 = effective constant force opposing piston motion

= preload + propellant pressure x area + friction + ...etc.

NOMENCLATURE

a = Area of solenoid valve orifice - in^2

A = Area of the actuator piston - in^2

C_D = Coefficient of discharge of the solenoid pilot valve orifice

C_P = Specific heat at constant pressure for the gas

C_V = Specific heat at constant volume for the gas

$$C_1 = \sqrt{\frac{2gK}{R(K-1)}} \qquad \frac{\sqrt{°R}}{SEC.}$$

$$C_2 = \sqrt{\frac{gK}{R\left(\frac{K+1}{2}\right)^{\frac{K+1}{K-1}}}} \qquad \frac{\sqrt{°R}}{SEC.}$$

F = The force acting on the piston rod in the opposite direction from the gas force

F = $\sum K_s Z$, f_p, $P_o A_o$, $P_f A_f$ etc. Where K_s = Spring rate, f_p = preload, P_o = pressure of oxidizer, A_o = area of oxidizer piston, P_f = pressure of fuel, A_f = area of fuel piston

g = Gravitational constant = Ft/sec^2

K = Ratio of specific heats

P = Pressure in the cylinder psi

P_s = Gas supply pressure psi

Q = Volumetric flow of gas in^3/sec

R = Gas constant ft-lb/lb °R

T_s = Gas temperature °R

V = Volume of cylinder in^3

$\mathring{W}$ = Mass flow of gas lb/sec

Z = Distance of piston travel from initial position in.

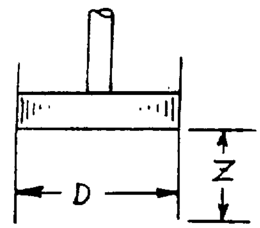
Z_o = Initial position of piston (from top of cylinder) in.

$= \frac{v}{A}$ where v = volume from top of piston to valve orifice

ρ = Gas density lb/in^3

APPENDIX C

Z/D OF PROPELLANT PISTON FOR MINIMUM CHANGE IN VOLUME DUE TO TOLERANCES OF STROKE (Z) AND PISTON DIAMETER (D)



Let the tolerance on D $=\triangle D$ and on Z $=\triangle Z$

Propellant volume $V = \frac{\pi}{4} D^2 Z$

$$\frac{\triangle V}{V} = 2\,\frac{\triangle D}{D} + \frac{\triangle Z}{Z}$$

$$= 2\,\frac{\triangle D}{D} + \frac{\pi D^2}{4V}\,\triangle Z$$

The root sum square error is

$$\frac{\triangle V}{V} = \sqrt{\frac{4}{D^2}(\triangle D)^2 + D^4\left(\frac{\pi \triangle Z}{4V}\right)^2}$$

The minimum value of the change in volume, $\frac{\triangle V}{V}$, is achieved when

$$\frac{d\,\frac{\triangle V}{V}}{d\,D} = 0$$

Performing the indicated operation results in

$$\frac{\triangle D}{D} = \frac{1}{\sqrt{2}}\,\frac{\triangle Z}{Z}$$

If $\triangle D = \triangle Z$

$$\frac{Z}{D} = \frac{1}{\sqrt{2}}$$

APPENDIX D

COMPARISON OF P.D.I. AND CONVENTIONAL SOLENOID VALVE SYSTEMS

The positive displacement injector and the conventional solenoid valve injector were compared based on the following conditions:

ΔI = Impulse bit = .1, .5, 1.0 lb. sec.

I_T = Total impulse = 1000; 10,000; 100,000; 250,000 lb. sec.

Propellants - N_2O_4 and 50% UDMH, 50% N_2H_4

I_{sp} = Theoretical specific impulse = 316 sec.

Specific impulse for pulse operation = .8 x 316 = 252.8 sec.

T = Operating temperature = 70°F

Temperature range 40 to 140°F

t = Pulse width = .010 sec.

P_c = Combustion chamber pressure - the optimum chamber pressure for minimum system weight varies with ΔI and I_T.

Table D.2 shows the pressures used.

Propellant flow rate in the conventional system to be controlled by cavitating venturies.

P_{FN} = Nitrogen feed pressure = 300 psi

In order to determine system weights it was necessary to determine the weight of the nitrogen used to actuate the P.D.I., the propellant weights of the two systems, and the weight and power requirements of the solenoid valves.

1. The weight of the nitrogen used to actuate the P.D.I. was determined by finding the weight of N_2 required per actuation, using the method of section IV-B-3 with the appropriate piston strokes, and then determining the number of actuations for each impulse bit and total impulse as shown in appendix E. The results are shown in Figure D.1.

2. In order to determine the propellant weights it was necessary to take into account the effects of errors in the oxidizer-fuel ratio and the specific impulse (appendix F). The results (Figure D.2) show that the P.D.I. requires slightly less propellant than the conventional system. For values of total impulse above 100,000 lb. sec. the difference is 2.6%.

3. Solenoid valve weight, power requirements and response are shown in Tables D.1 and D.2. The equivalent orifice diameters of the positive displacement injector pilot valves are for an actuation time of .01 seconds, and they were determined by the method used in section IV-B-3. The diameters of the valves for the conventional system are for a pressure drop of 50 psi thru the valve. The weight of a pulse shaper, for improving the response of the solenoid valve, is approximately 0.25 lb. per engine.

The two systems were also compared for impulse bit accuracy, oxidizer-fuel ratio accuracy, maximum operating frequency and stable limit cycle operation.

1. The P.D.I. has a smaller error in both impulse bit and oxidizer-fuel ratio for all values of total impulse for the 0.1 lb.sec. impulse bit and for a total impulse above 4000 lb. sec. for the larger impulse bits (Figures D.3 and D.4). Appendix G shows how these values were calculated.

2. The maximum operating frequencies of the two systems for a 0.010 second pulse width are shown in Figure D.5. The frequencies for the conventional system are for solenoid valves with pulse shaping because the 0.01 second pulse width could not be attained without it for the 0.5 and 1.0 lb. sec. impulse bits, as can be seen from the response times in Table D.2, unless power requirements were increased. To get a 50 percent increase in valve response, it is necessary to increase solenoid power by approximately 200 percent.

3. For stable limit cycle operation it is desirable to use the smallest possible impulse bit in order to keep propellant weight at a minimum. Large impulse bits are not practical because of the excessive amounts of propellants required to perform the same function as a small impulse bit. This can readily be seen in Figure D.6 which shows propellant weight vs. time for various impulse bits. For the 0.1 lb. sec. impulse bit the P.D.I. uses less propellant than the conventional system. The difference in propellant weight is 1.7 to 6.2 percent as the time increases from 10^5 to 10^8 seconds. The weight of nitrogen used to actuate the positive displacement injector is shown in Figure D.7. Appendix H shows how the above data was obtained.

WEIGHT OF NITROGEN USED TO ACTUATE PISTON VS TOTAL IMPULSE
FOR POSITIVE DISPLACEMENT INJECTOR

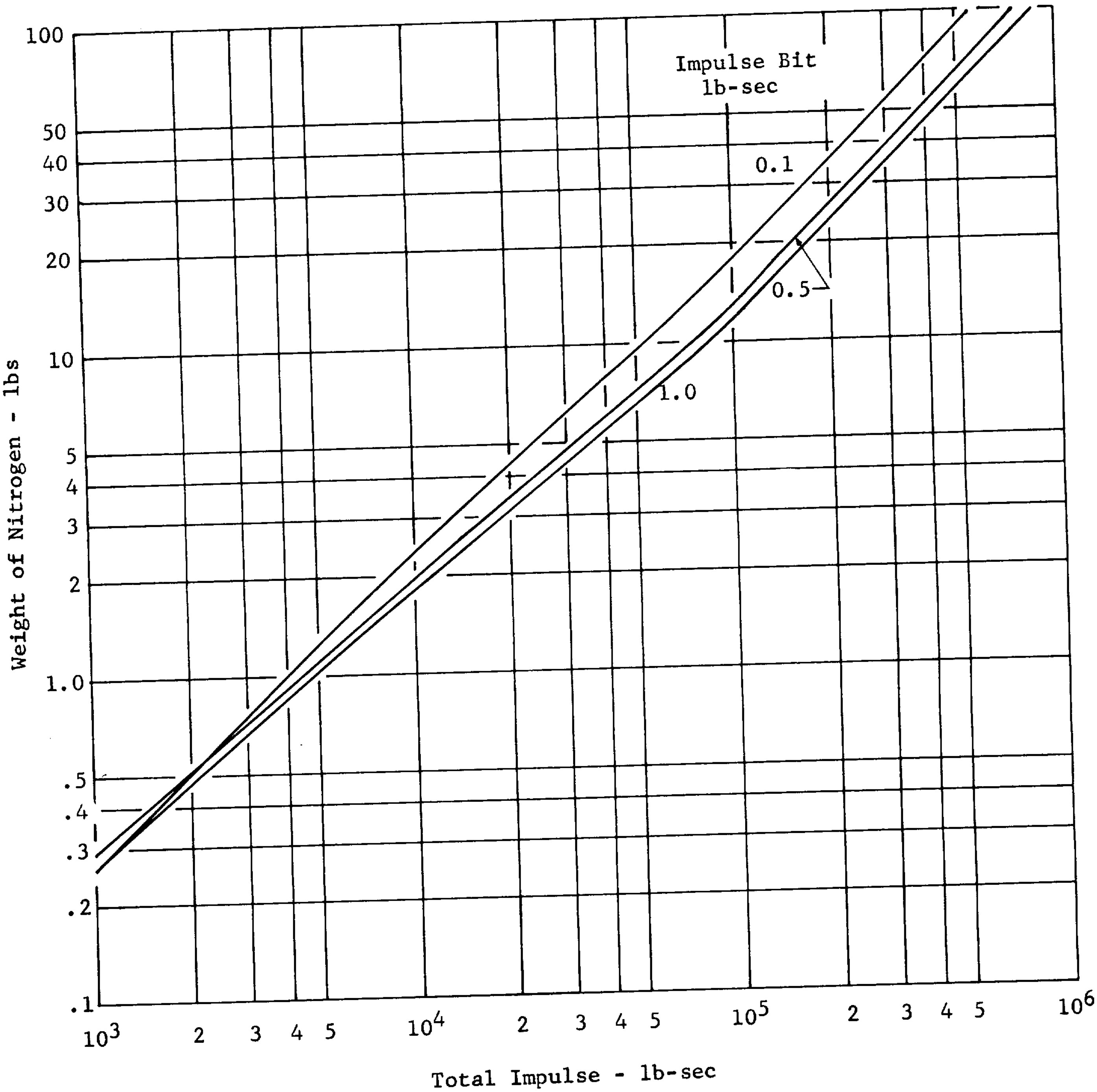
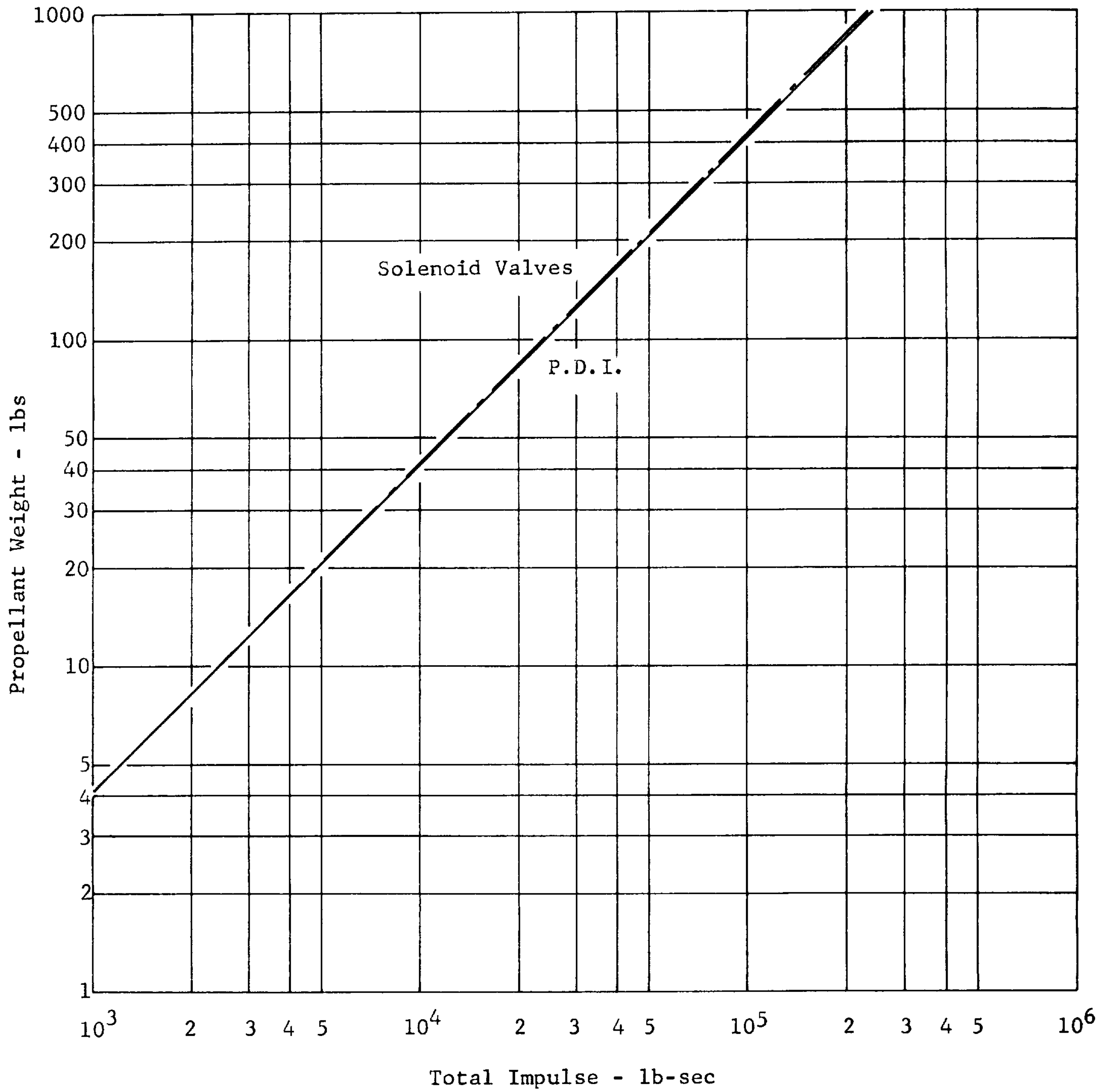


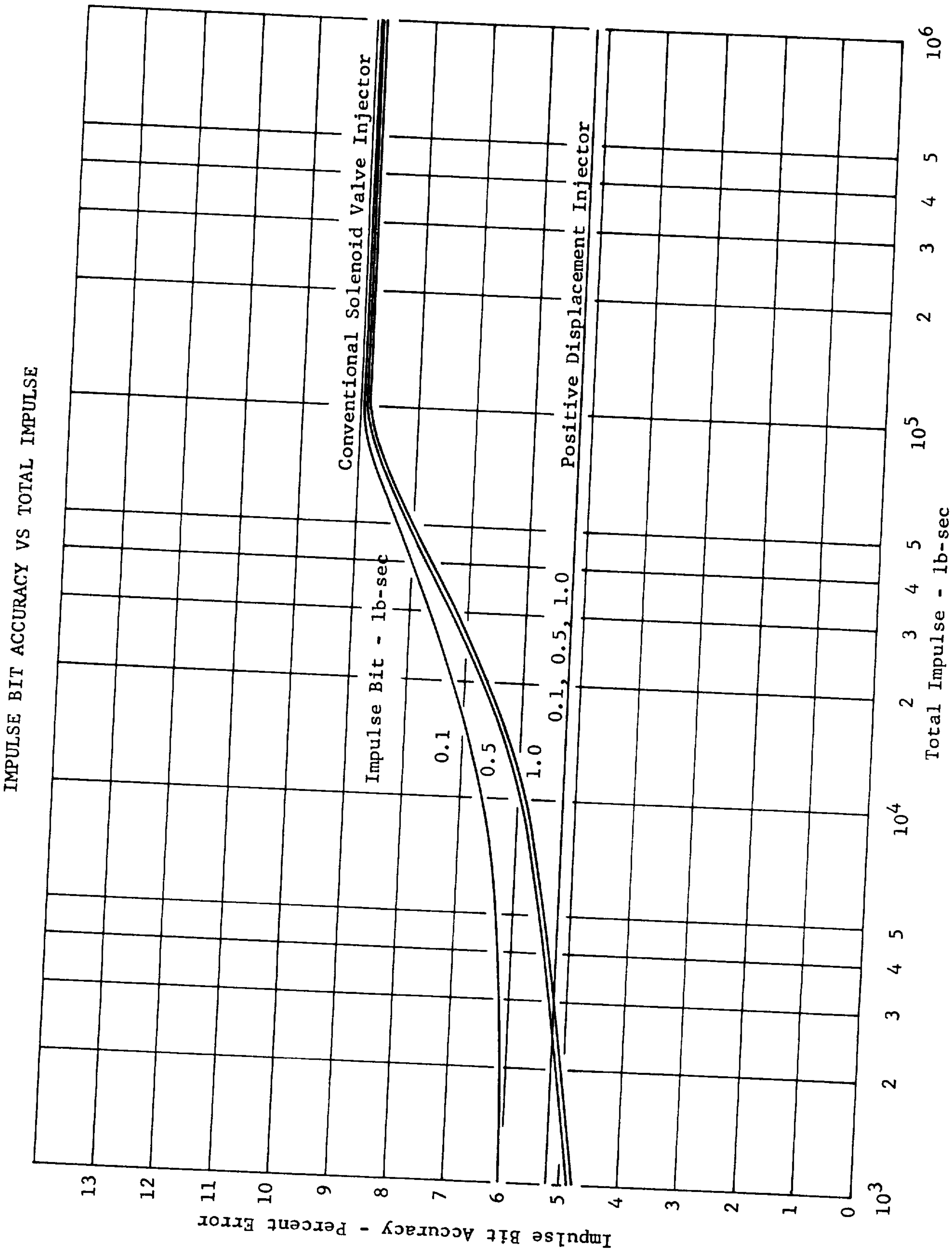
Figure D.1

PROPELLANT WEIGHT VS TOTAL IMPULSE



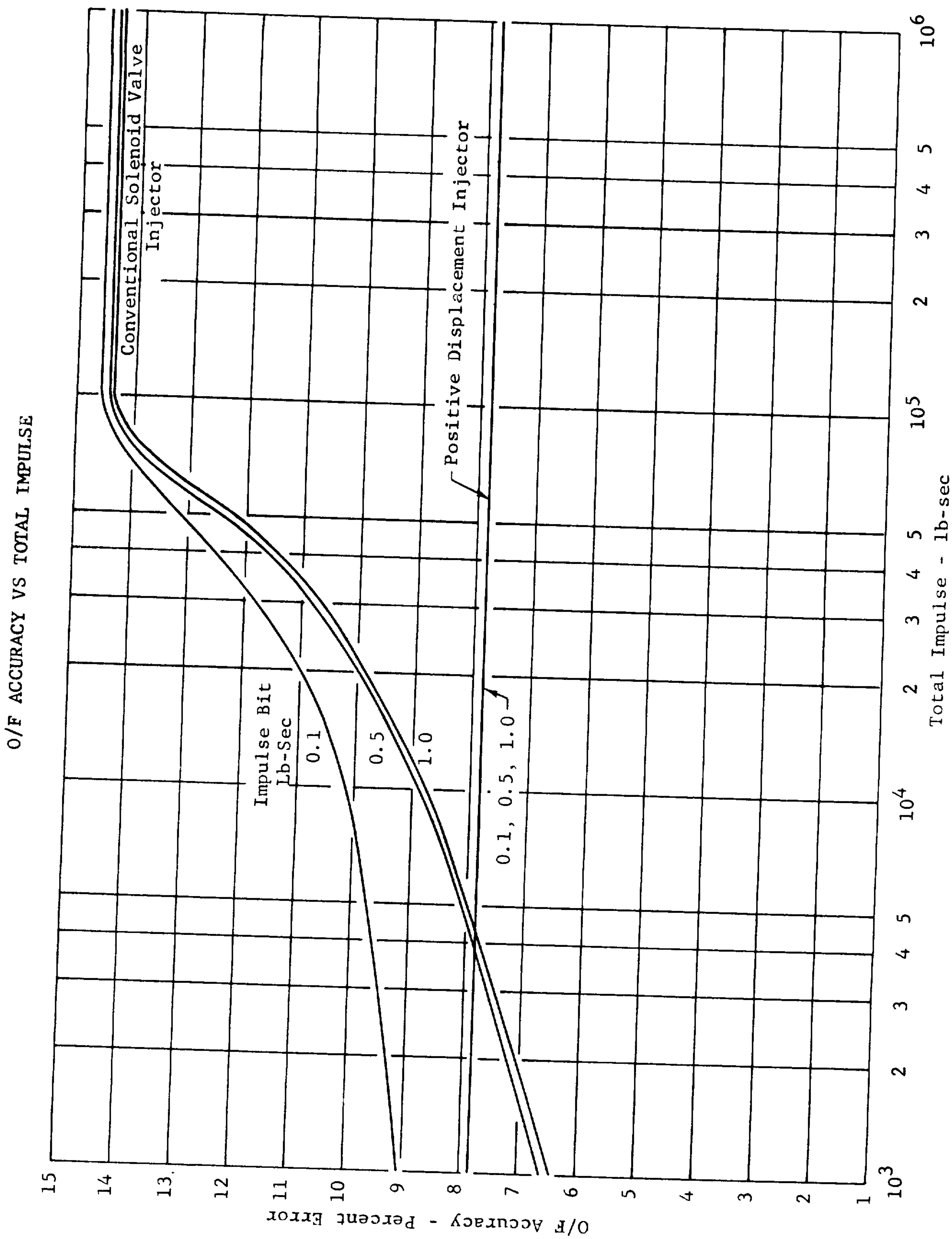
3299

Figure D.2



3322

Figure D.3



3324

Figure D.4

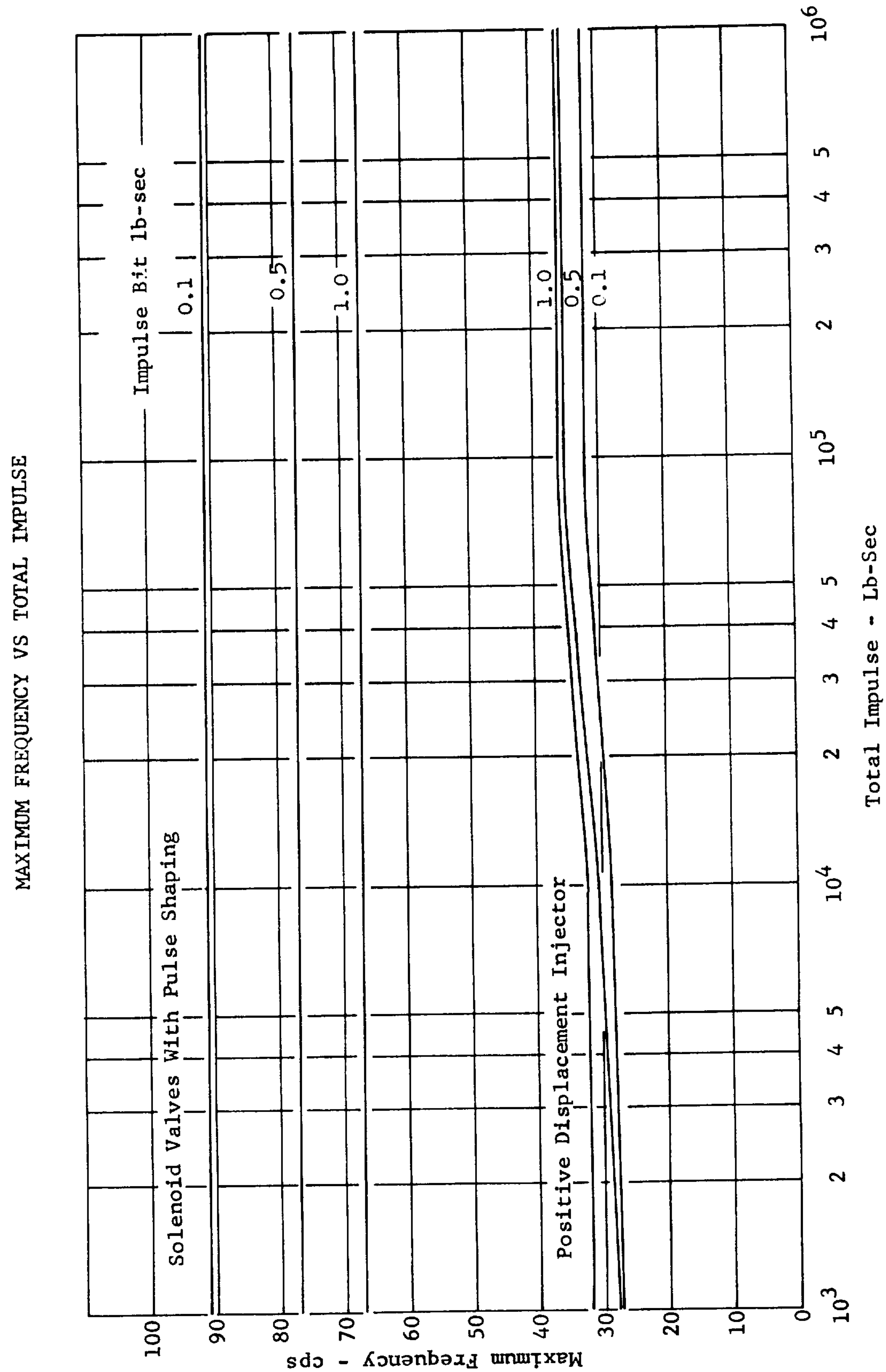

MAXIMUM FREQUENCY VS TOTAL IMPULSE
Impulse Bit lb-sec
0.1
0.5
1.0
Solenoid Valves With Pulse Shaping
Positive Displacement Injector
Maximum Frequency - cps
100
90
80
70
60
50
40
30
20
10
0
Total Impulse - Lb-Sec
10^3
2
3
4
5
10^4
10^5
10^6

Figure D.5

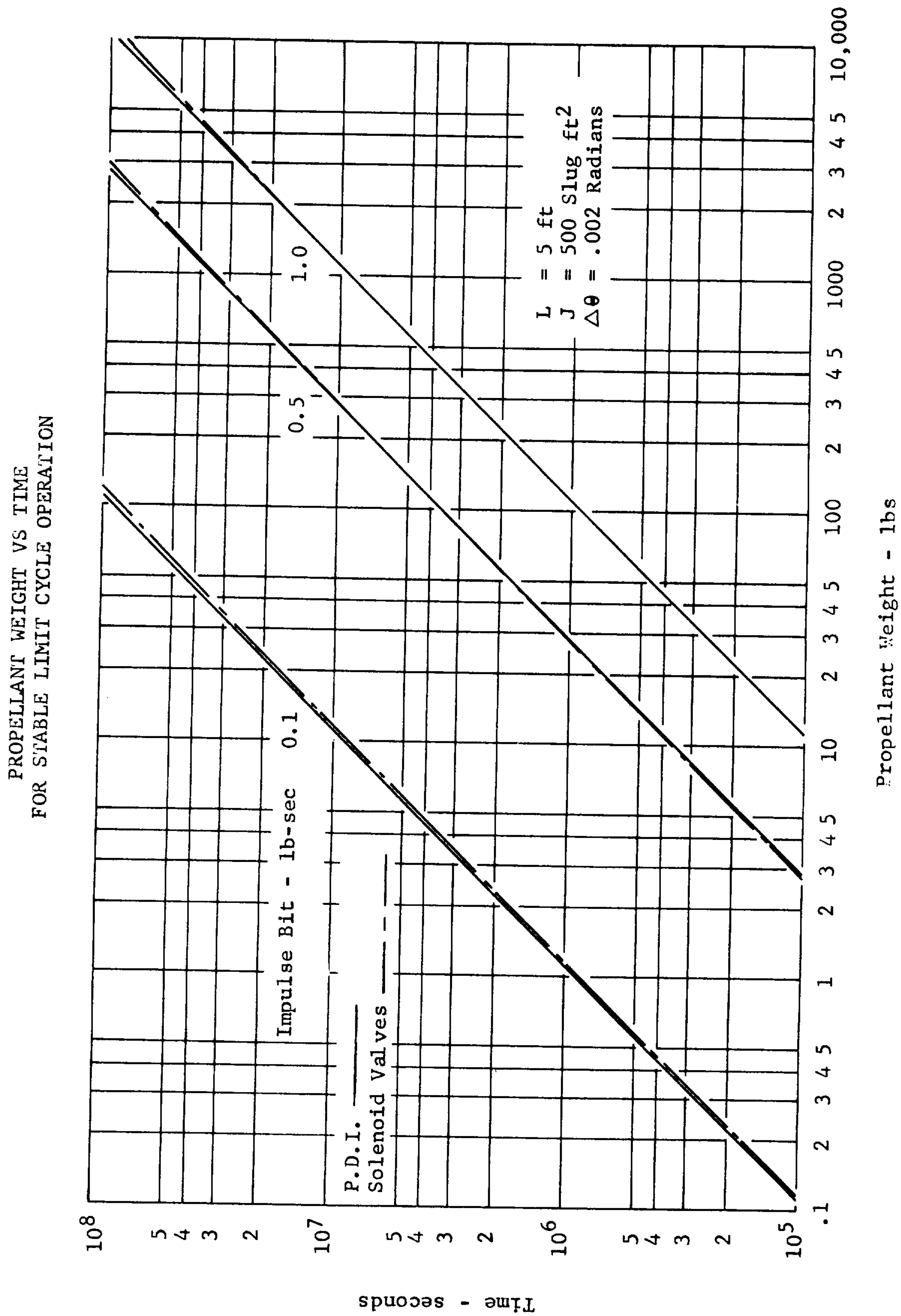
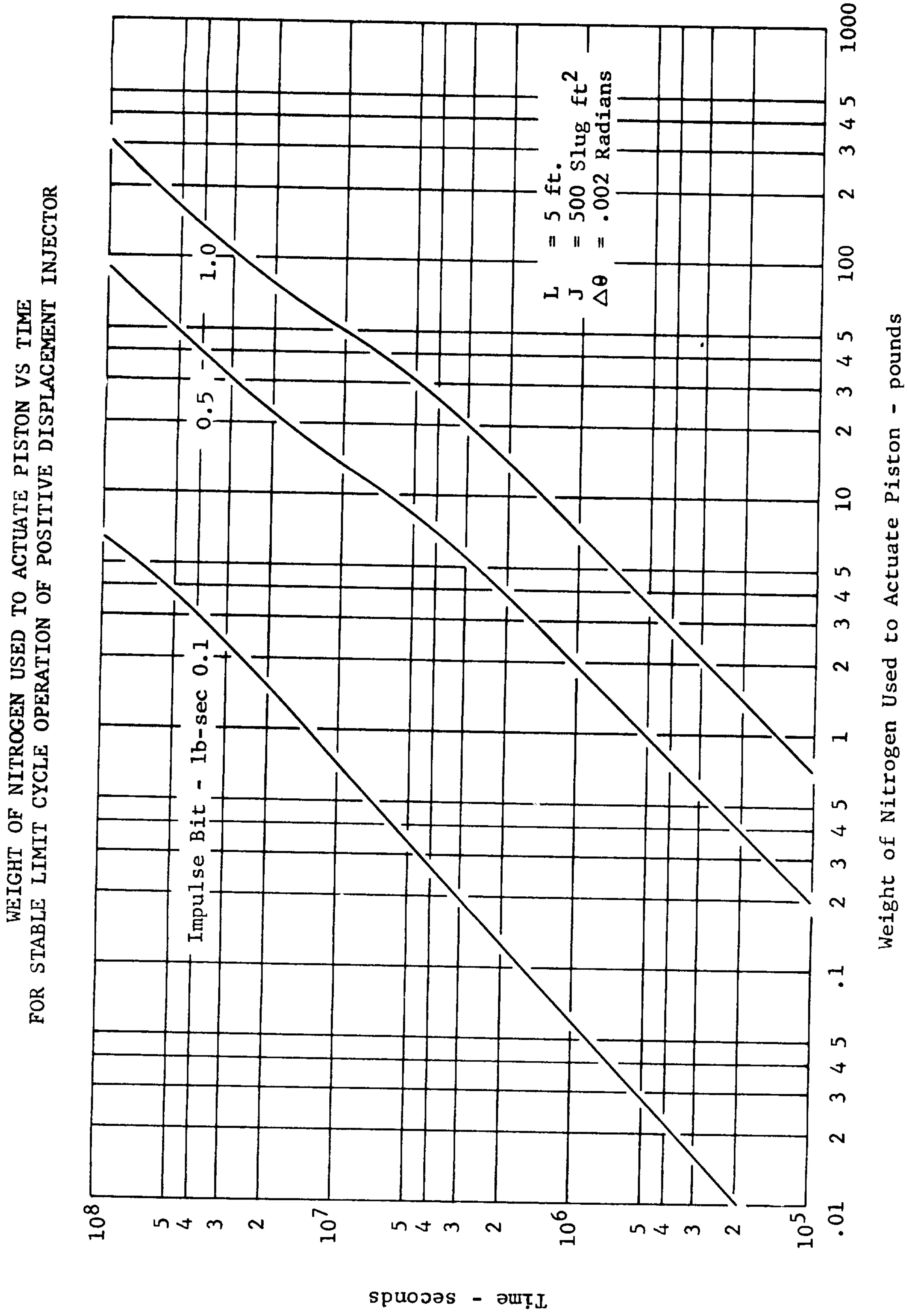


Figure D.6

3312



3313

Figure D.7

POSITIVE DISPLACEMENT INJECTOR
SOLENOID VALVE DATA

Impulse Bit Lb. Sec.			Total Impulse - lb. sec. 1,000	10,000	100,000 250,000
.1	(1) Equiv. Orifice Dia. - In.		.020	.019	.0167
	Weight lbs.		.15	.15	.15
	Power Watts		5	5	5
	Response without pulse shaping - sec.	Open (2) Close (3)	.005 .004	.005 .004	.005 .004
	Response with pulse shaping - sec.	Open Close	.001 .001	.001 .001	.001 .001
.5	Equiv. Orifice Dia. - In.		.051	.0425	.034
	Weight lbs.		.5	.5	.15
	Power Watts		10	9.5	7
	Response without pulse shaping - sec.	Open Close	.01 .01	.01 .01	.005 .005
	Response with pulse shaping - sec.	Open Close	.002 .003	.002 .003	.001 .001
1	Equiv. Orifice Dia. - In.		.073	.059	.048
	Weight lbs.		.7	.7	.5
	Power Watts		14	14	10
	Response without pulse shaping - sec.	Open Close	.014 .014	.014 .014	.01 .01
	Response with pulse shaping - sec.	Open Close	.003 .0035	.003 .0035	.002 .003

(1) $C_d = .9$
(2) Time from "on" signal to valve fully open
(3) Time from "off" signal to valve completely closed

Table D.1

CHAMBER PRESSURES FOR VARIOUS VALUES OF IMPULSE BIT AND TOTAL IMPULSE

Impulse Bit Lb. Sec.	Combustion Chamber Pressure - PSI			
	Total Impulse Lb. Sec.			
	1,000	10,000	100,000	250,000
.1	200	150	50	50
.5	400	200	50	50
1.0	400	200	50	50

SOLENOID VALVE CONTROLLED BIPROPELLANT
PULSE ENGINE PROPELLANT VALVE DATA

Impulse Bit	Solenoid Valve (1) Equiv. Orifice Dia.		Power Required per Valve	Weight per Valve	Valve Response Milliseconds			
					Without Pulse Shaping		With Pulse Shaping	
Lb-Sec	Oxidizer	Fuel	Watts	Lbs.	Open	Close	Open	Close
.1	.037	.041	5	.15	5	4	1	1
.5	.084	.089	14	.7	14	14	3	3.5
1.0	.117	.125	20	1.0	16	16	5	5

(1) $C_D = .65$

Table D.2

APPENDIX E

WEIGHT OF NITROGEN USED IN ACTUATING THE POSITIVE DISPLACEMENT INJECTOR

Total weight of N_2 used = $W_{NT} = W_{NA} m$

Where W_{NA} = Wt. of N_2 used per actuation

m = Number of actuations

$m = \dfrac{I_T}{\Delta I_{MIN.}}$ Where I_T = Total impulse, lb. sec.

$\Delta I_{MIN.}$ = Minimum value of the impulse bit

$$\Delta I_{min.} = \Delta I \left[1 - \frac{\Delta(\Delta I)}{\Delta I} \right] \qquad (1)$$

ΔI = Impulse bit, lb. sec.

$\dfrac{\Delta(\Delta I)}{\Delta I}$ = Error in the impulse bit, or impulse bit accuracy which is found as follows:

If it is assumed that the sensitivity of the specific impulse (I_{SP}) with respect to oxidizer-fuel ratio is negligible, then

$$W_T = W_o + W_f$$

Where W_T = Weight of propellant injected per stroke

W_o = Weight of oxidizer injected per stroke

W_f = Weight of fuel injected per stroke

$$W_T = V_o \rho_o + V_F \rho_F = \frac{\pi}{4} Z \left(D_o \rho_o + D_F \rho_F \right)$$

Where V_o = Volume of oxidizer injected per stroke

V_F = Volume of fuel injected per stroke

ρ_o = Density of the oxidizer

ρ_f = Density of the fuel

D_O = Diameter of the oxidizer injector piston

D_F = Diameter of the fuel injector piston

Z = Piston stroke

For optimum accuracy $D_o = \sqrt{2}\ Z$ (Appendix C)

$$\therefore\ W_T = \frac{\pi D_o}{4\sqrt{2}}\left(D_o^2 \rho_o + D_F^2 \rho_F\right)$$

$$\text{Now } \Delta I = W_T\ I_{SP} = \frac{\pi D_o I_{SP}}{4\sqrt{2}}\left(D_o^2 \rho_o + D_F^2 \rho_F\right) \tag{2}$$

$$\text{Then } \Delta(\Delta I) = \frac{\pi}{4\sqrt{2}}\Big[D_o I_{SP}\left(2 D_o \rho_o \Delta D_o + D_o^2 \Delta\rho_o + 2 D_F \rho_F \Delta D_F + D_F^2 \Delta\rho_F\right) + \left(D_o^2 \rho_o + D_F^2 \rho_F\right)\left(I_{SP}\Delta D_o + D_o \Delta I_{SP}\right)\Big] \tag{3}$$

Divide equation (3) by (2) and regroup terms to obtain (4)

$$\frac{\Delta(\Delta I)}{\Delta I} = \left[\frac{2}{1+\left(\frac{D_F^2 \rho_F}{D_o^2 \rho_o}\right)}\right]\frac{\Delta D_o}{D_o} + \left[\frac{2}{1+\left(\frac{D_o^2 \rho_o}{D_F^2 \rho_F}\right)}\right]\frac{\Delta D_F}{D_F} + \left[\frac{1}{1+\left(\frac{D_F^2 \rho_F}{D_o^2 \rho_o}\right)}\right]\frac{\Delta\rho_o}{\rho_o}$$

$$+ \left[\frac{1}{1+\left(\frac{D_o^2 \rho_o}{D_F^2 \rho_F}\right)}\right]\frac{\Delta\rho_F}{\rho_F} + \frac{\Delta I_{SP}}{I_{SP}} \tag{4}$$

To simplify this expression substitute A, B, C and D for the quantities within the brackets, then

$$\frac{\Delta(\Delta I)}{\Delta I} = A\frac{\Delta D_o}{D_o} + B\frac{\Delta D_F}{D_F} + C\frac{\Delta\rho_o}{\rho_o} + D\frac{\Delta\rho_F}{\rho_F} + \frac{\Delta I_{SP}}{I_{SP}} \tag{5}$$

A, B, C and D may be evaluated by using the oxidizer-fuel ratio, R

$$R = \frac{W_o}{W_F} = \frac{V_o \rho_o}{V_F \rho_F} = \frac{D_o^2 \rho_o}{D_F^2 \rho_F} = 1.4$$

Equation (5) will give the maximum impulse bit error, however it would be more realistic to use the RMS value of this error.

Thus:

$$\text{RMS}\ \frac{\Delta(\Delta I)}{\Delta I} = \left[A^2\left(\frac{\Delta D_o}{D_o}\right)^2 + B^2\left(\frac{\Delta D_F}{D_F}\right)^2 + C^2\left(\frac{\Delta \rho_o}{\rho_o}\right)^2 + D^2\left(\frac{\Delta \rho_F}{\rho_F}\right)^2 + \left(\frac{\Delta I_{sp}}{I_{sp}}\right)^2\right]^{\frac{1}{2}} \quad (6)$$

$\Delta D_o = \Delta D_f = .0002$ in.

D_o and D_f depend on the values of ΔI and I_{sp}

For an operating temperature of 70°F and a temperature range of 40° to 140°F

$$\frac{\Delta \rho_o}{\rho_o} = .0676 \quad (\text{for } N_2O_4)$$

$$\frac{\Delta \rho_F}{\rho_F} = .0391 \quad (\text{for 50-50 } N_2H_4 - \text{UDMH})$$

Let $\frac{\Delta I_{sp}}{I_{sp}} = .03$

The weight of nitrogen per actuation $W_{NA} = \frac{PV}{RT}$

Where $P = 300$ psi

$V = A\ (.1 + Z)$

A = Area of actuating piston

$R = 55.34$ Ft/°R

$T = 530$°R

APPENDIX F

PROPELLANT WEIGHT REQUIRED FOR A GIVEN TOTAL IMPULSE

The weight of propellant required for a given total impulse is

$W_T = \frac{I_T}{I_{sp}}$ Where I_T is the total impulse

If there are variations in specific impulse or oxidizer-fuel ratio (R), then additional propellant must be supplied to obtain the desired total impulse. The total weight of propellant required becomes:

$$W_T = \frac{I_T}{I_{sp}}\left(1 + \frac{\Delta W_T}{W_T}\right) \qquad (1)$$

$$\text{Where RMS } \frac{\Delta W_T}{W_T} = \sqrt{\left(\frac{\Delta W_T}{W_T}\right)_R^2 + \left(\frac{\Delta W_T}{W_T}\right)_{I_{sp}}^2} \qquad (2)$$

$W_T = \frac{I_T}{I_{sp}} \;\therefore\; \left(\frac{\Delta W_T}{W_T}\right)_{I_{sp}} = \frac{-I_T \Delta I_{sp}}{I_{sp}^2 W_T} = \frac{\Delta I_{sp}}{I_{sp}}$ = Error due to I_{sp} variation

$\left(\frac{\Delta W_T}{W_T}\right)_R = \frac{2R\left(\text{RMS } \frac{\Delta R}{R}\right)}{(1+R)^2}$ using RMS $\frac{\Delta R}{R}$ in equation (5) of Appendix I (3)

For the positive displacement injector

$$R = \frac{W_o}{W_F} = \frac{V_o \rho_o}{V_F \rho_F} \qquad (4)$$

$$\text{Then } \frac{\Delta R}{R} = \frac{\Delta \rho_o}{\rho_o} + \frac{\Delta V_o}{V_o} + \frac{\Delta \rho_F}{\rho_F} + \frac{\Delta V_F}{V_F}$$

$$\text{and RMS } \frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta \rho_o}{\rho_o}\right)^2 + \left(\frac{\Delta V_o}{V_o}\right)^2 + \left(\frac{\Delta \rho_F}{\rho_F}\right)^2 + \left(\frac{\Delta V_F}{V_F}\right)^2} \qquad (5)$$

Substitute (5) into (3) to obtain the error due to changes in O/F ratio $\left(\frac{\Delta W_T}{W_T}\right)_R$ for the P.D.I.

For a conventional solenoid valve injector

$$R = \frac{\dot{W}_o}{\dot{W}_F} \quad \text{and} \frac{\Delta R}{R} = \left(\frac{\Delta \dot{W}_o}{\dot{W}_o}\right) - \left(\frac{\Delta \dot{W}_F}{\dot{W}_F}\right)$$

$$\text{and RMS} \frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta \dot{W}_o}{\dot{W}_o}\right)^2 + \left(\frac{\Delta \dot{W}_F}{\dot{W}_F}\right)^2} \tag{6}$$

When the propellant flow rate is controlled by cavitating venturies

$$\dot{W}_o = C_D A_o \sqrt{2 g \rho_o} \sqrt{P_F - P_{VO}} \tag{7}$$

and

$$\dot{W}_F = C_D A_F \sqrt{2 g \rho_F} \sqrt{P_F - P_{VF}} \tag{8}$$

Where A_o and A_f are the throat areas of the venturies

P_f = Propellant feed pressure

P_{vo} and P_{vf} are the oxidizer and fuel vapor pressure

From equations (7) and (8) the RMS errors are

$$\text{RMS} \frac{\Delta \dot{W}_o}{\dot{W}_o} = \left[\left(\frac{\Delta C_D}{C_D}\right)^2 + \left(\frac{\Delta A_o}{A_o}\right)^2 + \left(\frac{\Delta \rho_o}{2 \rho_o}\right)^2 + \left(\frac{P_F}{2[P_F - P_{VO}]} \frac{\Delta P_F}{P_F}\right)^2 + \left(\frac{P_{VO}}{2[P_F - P_{VO}]} \frac{\Delta P_{VO}}{P_{VO}}\right)^2\right]^{\frac{1}{2}} \tag{9}$$

$$\text{RMS} \frac{\Delta \dot{W}_F}{\dot{W}_F} = \left[\left(\frac{\Delta C_D}{C_D}\right)^2 + \left(\frac{\Delta A_F}{A_F}\right)^2 + \left(\frac{\Delta \rho_o}{2 \rho_o}\right)^2 + \left(\frac{P_F}{2[P_F - P_{VF}]} \frac{\Delta P_F}{P_F}\right)^2 + \left(\frac{P_{VF}}{2[P_F - P_{VF}]} \frac{\Delta P_{VF}}{P_{VF}}\right)^2\right]^{\frac{1}{2}} \tag{10}$$

In (9) and (10) let $\left(\frac{\Delta C_D}{C_D}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 = .0001$

$$\frac{\Delta P_F}{P_F} = .02$$

For 40° to 140°F temperature range $\frac{\Delta P_{VO}}{P_{VO}} = 3.93$ and $\frac{\Delta P_{VF}}{P_{VF}} = 3.73$

At 70°F $P_{VO} = 15$ PSIA and $P_{VF} = 2.2$ PSIA

$$P_f = P_c + \Delta P_{injector} + \Delta P_{valve} + \Delta P_{venturi}$$

In this study

P_c varies with ΔI and I_T (Table D.2)

$\Delta P_{injector} = 97$ psi

$\Delta P_{valve} = 50$ psi

$\Delta P_{venturi} = 0.15\, P_f$

APPENDIX G

IMPULSE BIT AND O/F RATIO ACCURACY

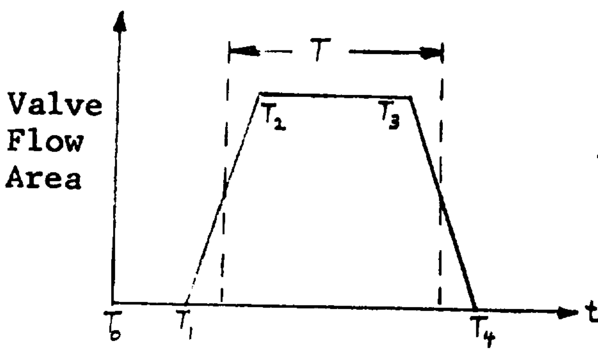
I. Impulse Bit Accuracy

A. For the P.D.I. the impulse bit accuracy is given by equation (6) in Appendix E.

B. For the conventional solenoid valve injector system, the impulse bit accuracy is determined as follows:

The impulse bit $\Delta I = I_{sp} W_T = \int F\,dt$

Where F = Thrust
t = Time
$W_T = W_o + W_f$ for each pulse
$W_o = \dot{W}_o T$ and $W_f = \dot{W}_f T$
T = Time propellant is flowing = Time the valve is open
$\dot{W}_o$ and $\dot{W}_f$ are the oxidizer and fuel weight flow rates.



$$T = \left(\frac{T_2 - T_1}{2}\right) + (T_3 - T_2) + \left(\frac{T_4 - T_3}{2}\right)$$

$$\int F\,dt = F_o \int_0^T \left(1 - e^{-\frac{t}{\tau_b}}\right) dt + F_i \int_0^\infty e^{-\frac{t}{\tau_d}}\, dt \qquad (1)$$

$$F_i = F_o\left(1 - e^{-\frac{t}{\tau_b}}\right) \qquad (2)$$

Substituting equation (2) into (1)

$$\Delta I = \int F\,dt = F_o \int_0^T (1 - e^{-t/\tau_b}) + F_o(1 - e^{-T/\tau_b}) \int_0^\infty e^{-t/\tau_d}\,dt$$

$$= F_o\left[T + (\tau_d - \tau_b)(1 - e^{-T/\tau_b})\right] \quad (3)$$

Then $$\Delta(\Delta I) = F_o\left[\Delta T + (\tau_d - \tau_b)\left(\frac{1}{\tau_b} e^{-T/\tau_b}\right)\Delta T\right] + \Delta F_o\left[T + (\tau_d - \tau_b)(1 - e^{-T/\tau_b})\right] \quad (4)$$

From (4) and (3)

$$RMS\ \frac{\Delta(\Delta I)}{\Delta I} = \left[\left(\frac{T + (\tau_d - \tau_b)\left(\frac{T}{\tau_b}\right)\left(e^{-T/\tau_b}\right)}{T + (\tau_d - \tau_b)(1 - e^{-T/\tau_b})}\ \frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta F_o}{F_o}\right)^2\right]^{\frac{1}{2}} \quad (5)$$

Where τ_b = thrust buildup time constant
τ_d = thrust decay time constant

If cavitating venturies are used, the propellant flow rate will be independent of the pressure downstream of the venturi and will result in $\tau_d = \tau_b$

$$\therefore\ RMS\ \frac{\Delta(\Delta I)}{\Delta I} = \left[\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta F_o}{F_o}\right)^2\right]^{\frac{1}{2}} \quad (6)$$

Where ΔT = .0003 sec. $\quad T$ = .01 sec.

$F_o = \mathring{W}_t\, I_{sp}$ from which

$$RMS\ \frac{\Delta F_o}{F_o} = \left[\left(\frac{\Delta \mathring{W}_T}{\mathring{W}_T}\right)^2 + \left(\frac{\Delta I_{sp}}{I_{sp}}\right)^2\right]^{\frac{1}{2}} \quad (7)$$

NOW $\mathring{W}_t = \mathring{W}_o + \mathring{W}_f$

$$\therefore \frac{\Delta \dot{W}_T}{\dot{W}_T} = \frac{\dot{W}_o}{\dot{W}_o + \dot{W}_f} \frac{\Delta \dot{W}_o}{\dot{W}_o} + \frac{\dot{W}_f}{\dot{W}_o + \dot{W}_f} \frac{\Delta \dot{W}_f}{\dot{W}_f}$$

$$\text{O/F Ratio} = R = \frac{\dot{W}_o}{\dot{W}_f}$$

$$\text{Then RMS } \frac{\Delta \dot{W}_T}{\dot{W}_T} = \left[\left(\frac{R}{R+1} \frac{\Delta \dot{W}_o}{\dot{W}_o}\right)^2 + \left(\frac{1}{R+1} \frac{\Delta \dot{W}_f}{\dot{W}_f}\right)^2\right]^{\frac{1}{2}} \qquad (8)$$

$\frac{\Delta \dot{W}_o}{\dot{W}_o}$ and $\frac{\Delta \dot{W}_f}{\dot{W}_f}$ are given by equations (9) and (10) in Appendix F.

II. Oxidizer-Fuel Ratio Accuracy

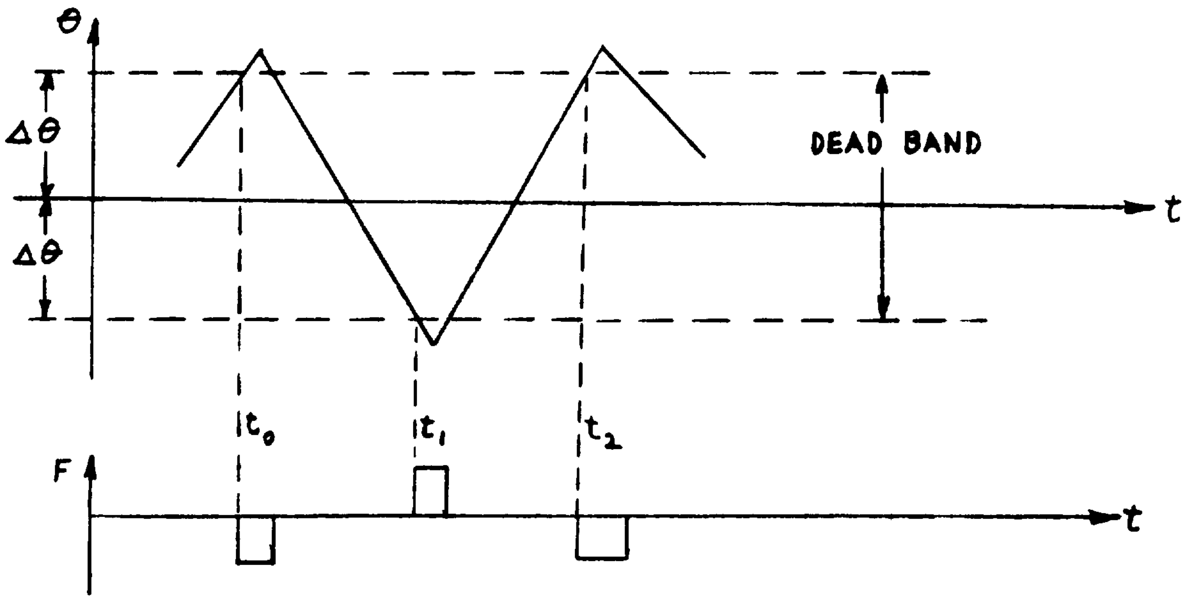
A. The O/F ratio accuracy of the P.D.I. is given by equation (5) of Appendix F.

B. The O/F ratio accuracy of the conventional system is given by equation (6) of Appendix F.

APPENDIX H

STABLE LIMIT CYCLE OPERATION

The time domain of the stable limit cycle is shown in the following figure:



Assume the angular velocity between t_0 and t_1 is $\dot{\theta}_1$

$$\therefore \quad t_1 - t_0 = \frac{-2\Delta\theta}{-\dot{\theta}_1} = \frac{2\Delta\theta}{\dot{\theta}_1}$$

At $t = t_1$ a velocity impulse of $\Delta\dot{\theta}$ is added to the vehicle

$$\therefore \quad \dot{\theta}_2 = \Delta\dot{\theta} - \dot{\theta}_1$$

Where $\dot{\theta}_2$ is the angular velocity between t_1 and t_2

$$\therefore \quad t_2 - t_1 = \frac{2\Delta\theta}{\Delta\dot{\theta} - \dot{\theta}_1}$$

The time to complete one cycle, t', is given by

$$t' = t_2 - t_0 = (t_2 - t_1) + (t_1 - t_0)$$

$$t' = \frac{2\Delta\theta}{\dot{\theta}_1} + \frac{2\Delta\theta}{\Delta\dot{\theta} - \dot{\theta}_1}$$

$$= \frac{2\Delta\theta(\Delta\dot{\theta})}{\dot{\theta}_1(\Delta\dot{\theta} - \dot{\theta}_1)}$$

$$\Delta\dot{\theta} = \frac{\Delta I \ell}{J}$$

Where I = Impulse bit
l = Moment arm of the engine
J = Vehicle moment of inertia

The propellant used per impulse, w, is given by

$$w = I_t/I_{sp}$$

and the average propellant consumption rate is given by

$$\dot{w} = \frac{2w}{t'}$$

Since there are two impulses per cycle

$$\dot{w} = \left(\frac{2\Delta I}{I_{sp}}\right)\left(\frac{\dot{\theta}_1[\Delta\dot{\theta} - \dot{\theta}_1]}{2\Delta\theta[\Delta\dot{\theta}]}\right)$$

For a system where the impulse bit is independent of the angular error of the vehicle (such as the P.D.I. which has a constant impulse bit); the vehicle will not necessarily converge to a symmetrical limit cycle. Then $\dot{\theta}_1$ may vary between 0 and $\Delta\dot{\theta}$ depending on the initial conditions prior to the limit cycle operation.

Assuming $\dot{\theta}_1$ constant over the range $0<\dot{\theta}_1<\Delta\dot{\theta}$, the average propellant consumption becomes:

$$\dot{W}_{AVE.} = \frac{1}{\Delta\dot{\theta}}\int_0^{\Delta\dot{\theta}} \left(\frac{\Delta I}{I_{sp}\,\Delta\theta} \times \frac{\dot{\theta}_1(\Delta\dot{\theta}-\dot{\theta}_1)}{\Delta\dot{\theta}} \right) d\dot{\theta}_1$$

$$= \frac{\Delta I\,\Delta\dot{\theta}}{6\,I_{sp}\,J\,\Delta\theta}$$

$$\dot{W}_{AVE.} = \frac{(\Delta I)^2 \lambda}{6\,I_{sp}\,J\,\Delta\theta} \qquad (1)$$

$$\frac{\Delta\dot{W}_{AVE.}}{\dot{W}_{AVE.}} = \frac{6\,I_{sp}J\Delta\theta}{(\Delta I)^2\lambda}\left[\frac{2\lambda\Delta I\,\Delta(\Delta\theta)}{6\,I_{sp}\,J\,\Delta\theta} - \frac{\Delta I_{sp}(\Delta I)^2\lambda}{6\,I_{sp}^2\,J\,\Delta\theta}\right]$$

$$= 2\,\frac{\Delta(\Delta I)}{\Delta I} - \frac{\Delta I_{sp}}{I_{sp}}$$

Then RMS $$\frac{\Delta\dot{W}_{AVE.}}{\dot{W}_{AVE.}} = \left[4\left(\frac{\Delta(\Delta I)}{\Delta I}\right)^2 + \left(\frac{\Delta I_{sp}}{I_{sp}}\right)^2\right]^{\frac{1}{2}} \qquad (2)$$

Combining equations (1) and (2) the total average flow rate of the propellant becomes

$$\dot{W}_{AVE.,T} = \dot{W}_{AVE}\left(1 + RMS\,\frac{\Delta\dot{W}_{AVE.}}{\dot{W}_{AVE.}}\right) \qquad (3)$$

The total weight of propellant required is given by

$$W_T = \left(\dot{W}_{AVE.,T}\right)T \qquad (4)$$

Where T is the length of time in stable limit cycle operation

In this study $\ell = 5$ Ft., J = 500 slug ft^2, $\Delta\theta = .002$ radians.

For the conventional system $\frac{\Delta(\Delta I)}{\Delta I}$ for equation (2) is obtained from equation (6) of Appendix G.

For the P.D.I. $\frac{\Delta(\Delta I)}{\Delta I}$ in equation (2) is obtained from equation (6) of Appendix E.

The weight of nitrogen used to actuate the P.D.I. is given by

$$W_{N_2} = \frac{PA(Z+.1)}{RT} \qquad \text{(per pulse)}$$

Where A = The area of the actuating piston
Z = Piston stroke
R = 55.34 ft/°R
T = 530°R

For the length of time of limit cycle operation "T" this becomes

$$W_{N_2,T} = \frac{PA(Z+.1)\, m}{RT}$$

Where $m = \frac{W_t}{W}$ = The number of pulses in time T

$W = \frac{\Delta I}{I_{sp}}$ = Weight of propellant per pulse

$$\therefore W_{N_2T} = \frac{PA(Z+.1)\, W_t\, I_{sp}}{RT\Delta I} \tag{5}$$

W_t is obtained from (4)

APPENDIX I

PROPELLANT WEIGHT REQUIREMENTS - O/F RATIO DEVIATION

If the oxidizer-fuel ratio deviates from its design value (R) during engine operation some extra propellant must be carried to insure that the desired total impulse will be obtained.

Oxidizer weight $W_o = \frac{W_t}{1+R}$

Fuel Weight $W_f = \frac{W_t R}{1+R}$ Where W_t = Total propellant weight.

With an error in O/F ratio of ΔR, the O/F ratio will vary from $R\left(1+\frac{\Delta R}{R}\right)$ to $R\left(1-\frac{\Delta R}{R}\right)$.

Extra oxidizer will be needed in the first case and extra fuel in the second.

The extra oxidizer is given by

$$\Delta W_o = \frac{W_t R\left(1+\frac{\Delta R}{R}\right)}{1+R\left(1+\frac{\Delta R}{R}\right)} - W_t \frac{R}{1+R} \tag{1}$$

The extra fuel is given by

$$\Delta W_f = \frac{W_t}{1+R\left(1-\frac{\Delta R}{R}\right)} - \frac{W_t}{1+R} \tag{2}$$

Then $\Delta W_t = \Delta W_o + \Delta W_f$ (3)

$$= W_t\left[\frac{R\left(1+\frac{\Delta R}{R}\right)}{1+R\left(1+\frac{\Delta R}{R}\right)} + \frac{1}{1+R\left(1-\frac{\Delta R}{R}\right)} - 1\right] \tag{4}$$

Since ΔR is usually in the range of .01 to .05 and is therefore very much smaller than 1+R, equation (4) reduces to:

$$\frac{\Delta W_t}{W_t} = \frac{2R\left(\frac{\Delta R}{R}\right)}{(1+R)^2} \qquad (5)$$

Equation (5) may be used when $\frac{\Delta R}{R}$ is very much smaller than 1+R.

APPENDIX J

REACTION WHEEL SYSTEM - PRELIMINARY SYSTEM DESIGN

The following analysis was used co evaluate the weight of a single axis reaction wheel system. This type of system is capable of using solar energy to supply a maximum power requirement (not total energy) whereas a comparable mass expulsion system must carry its total energy in propellant weight.

The system parameters are shown in the following analysis. The selection of a disturbance, a wheel radius, and a response time defines the system for various final angular velocities of the wheel. The assumption of a disturbance of 1/2 of a pulse of the attitude control engine (110# thrust) resulted in unrealistic weights for wheels less than 20 ft. in diameter. Thus the assumption of a disturbance equal to 1.1# thrust at the 75 ft. vehicle radius was used. This resulted in the following:

Wheel radius	=	1.0 Ft.
System response	=	0.010 sec.
Final (max.) velocity	=	1.0 rad/sec.

System Weight:

Single axis	=	72#
Three axes	=	216#

Specification:

1. Scope:

   Sizing of a reaction wheel system for vernier control of a space station. Analysis to be based on the weight of wheel, motor and energy supply.

2. References:

   a. Kurzhals, P.R. and Adams, J.J., "Dynamics and Stabilization of the Rotating Space Station", Astronautics, Sept. 1962, pp 25-29.

b. Finver, B., "Inertia Wheel Attitude Control", Internal Memorandum, W.A.D., 11/7/62.

c. Adams, J.J. and Chilton, R.G., "A Weight Comparison of Several Attitude Controls for Satellites", NASA Memo 12/30/58L.

3. Operation:

a. For any disturbances to or motions required by the vehicle the attitude control mode will provide gross correction and the vernier mode will provide fine correction.

b. The vernier mode shall be capable of removing the torque imparted to the vehicle by one pulse of the attitude control mode (2x110x75).

4. Physical Properties:

a. Vehicle:

Weight: 150,000 #
Dia. 150 ft.
Moment of inertia in plane axis = 10,500,000 slug ft^2

b. Attitude Control Mode:

I_T = 140,000 # sec
Thrust = 110#
I_{bit} = 1.1 # sec

c. Vernier Control Mode:

I_T = 375,000 # sec
Thrust = 1.1#
I_{bit} = .011 # sec

5. Ambient Conditions:

Space

6. Electrical:

See Motor Weight Analysis

7. Notes:

a. Modification of item (3) may be required to provide realistic analysis.

b. Analysis will consider single body axis only and will neglect gyroscopic interactions.

Analysis:

Symbols:

I - Moment of inertia - slug ft^2
$\ddot{\theta}$ - Angular acceleration - rad/sec^2
$\dot{\theta}$ - Angular velocity - rad/sec
M - Torque - ft. #
g - Gravitational constant
W - Weight - #
t - Time - Sec
σ - Material hoop stress - 120,000 psi
γ - Material density - #/in^3
P - Power - ft.#/sec
E - Energy - Ft. #
r - Radius - Ft.

Subscripts:

w - Wheel
s - Satellite vehicle

Equations:

For a single vehicle axis

$$I_s \ddot{\theta}_s = I_w \ddot{\theta}_w = M$$

$$\dot{\theta}_w = \int_0^t \ddot{\theta}_w \, dt = \int_0^t \ddot{\theta}_s \frac{I_s}{I_w} \, dt = \int_0^t \frac{M}{I_w} \, dt$$

for M = Constant

$$\dot{\theta}_w I_w = M \Delta t \qquad \text{(1)}$$

where Δt corresponds to the number of times the minimum impulse bit is utilized (at .010 $\frac{\text{seconds}}{\text{bit}}$).

Wheel weight:

$$W_w = \frac{I_w g}{r_w^2}$$

and

$$r_w \le \sqrt{\frac{\sigma g}{\gamma \dot{\theta}_w^2}}$$

using a .9 safety factor

$$r_w = .9\sqrt{\frac{\sigma g}{\gamma \dot{\theta}_w^2}}$$

thus

$$W_w = \frac{I_w \gamma \dot{\theta}_w^2}{(.9)^2 \sigma} = \frac{M \Delta t \gamma \dot{\theta}_w}{(.9)^2 \sigma} \qquad \text{— — — — — (2)}$$

and the radius of the wheel

$$r_w = \sqrt{\frac{I_w g}{W_w}} \qquad \text{— — — — — (3)}$$

Note: Utilizing other inputs of equation (1) provides the minimum wheel weight and, thus, the largest radius - the same conditions (equation 1) may be satisfied by allowing the W_W to increase by 100 and thus reducing the r_W by 10. (See Fig. J.1)

Power:

$$P_{MAX.} = I_w \ddot{\theta}_w \dot{\theta}_w = M \dot{\theta}_w \qquad \text{— — — — — — (4)}$$

This is the power required for acceleration of the wheel to its maximum velocity.

Energy:

$$E = \frac{P_{MAX}}{2} \Delta t = \overline{P} \Delta t \qquad \text{— — — — — — (5)}$$

$$\Delta t = \frac{\text{Total Impulse}}{\text{Impulse Bit Thrust}}$$

Component Weights:

Motor: $W_M = f\ (HP)$

See Figure J.2 — — — — — — — (6)

Solar Cells: $W_{SC} = f\ (\text{watts})$

From Ref. "C" $0.3\ \frac{\#}{\text{watt}}$ — — — — — (7)

for constant solar orientation

Batteries:

$W_B = f\ (\text{total energy})$

See Figure J.3 — — — — — — — (8)

A realistic system would use the solar cells as a primary power supply with only a small battery system, (Ref. "C").

Thus: $W_{\substack{\text{power}\\\text{supply}}} = 0.4\ \frac{\#}{\text{watt}}$ — — — — — — (9)

The following is a weight analysis for two disturbing torques.

Case 1. $M_{MAX.} \doteq \frac{1}{2} \times 110\#\ \text{THRUST} \times 75\ \text{FT. RADIUS} = 4125\ \text{FT}\#$

$$\Delta t = \frac{100}{2}(.010) = 0.50\ \text{SEC.}$$

Case 2. $M_{MAX.} = 1 \times 1.1\#\ \text{THRUST} \times 75\ \text{FT. RADIUS} = 82.5\ \text{FT}\#$

$$\Delta t = 1(.010) = .010\ \text{SEC.}$$

Case 1. corresponds to the initially assumed conditions (see par. 3b) modified to a maximum torque of 1/2 of one engine firing.

It is observed that the reaction wheel weight is insignificant Also, the corresponding radii are physically unrealistic.

Thus the weights were recomputed for a 1.0 ft. radius wheel with the same moment of inertia. (See equation 3).

Case 3. $M = 4125$ ft #

$\Delta t = 0.5$ sec.

$r_w = 1.0$ ft

Case 4. $M = 82.5$ ft #

$\Delta t = 0.010$ sec.

$r_w = 1.0$ ft

Further, in equation (1), the Δt can be defined as the reaction wheel system response as opposed to the present impulse bit definition.

Thus:

Case 5. $M = 4125$ ft #

$\Delta t = 0.010$ sec.

$r_w = 1.0$ ft

This Δt becomes unrealistic for motors > 0.1 HP - however the data is included for comparison.

The weights for the above cases are tabulated in tables J.1 and J.2.

REACTION WHEEL CHARACTERISTICS

I_W vs. W_W

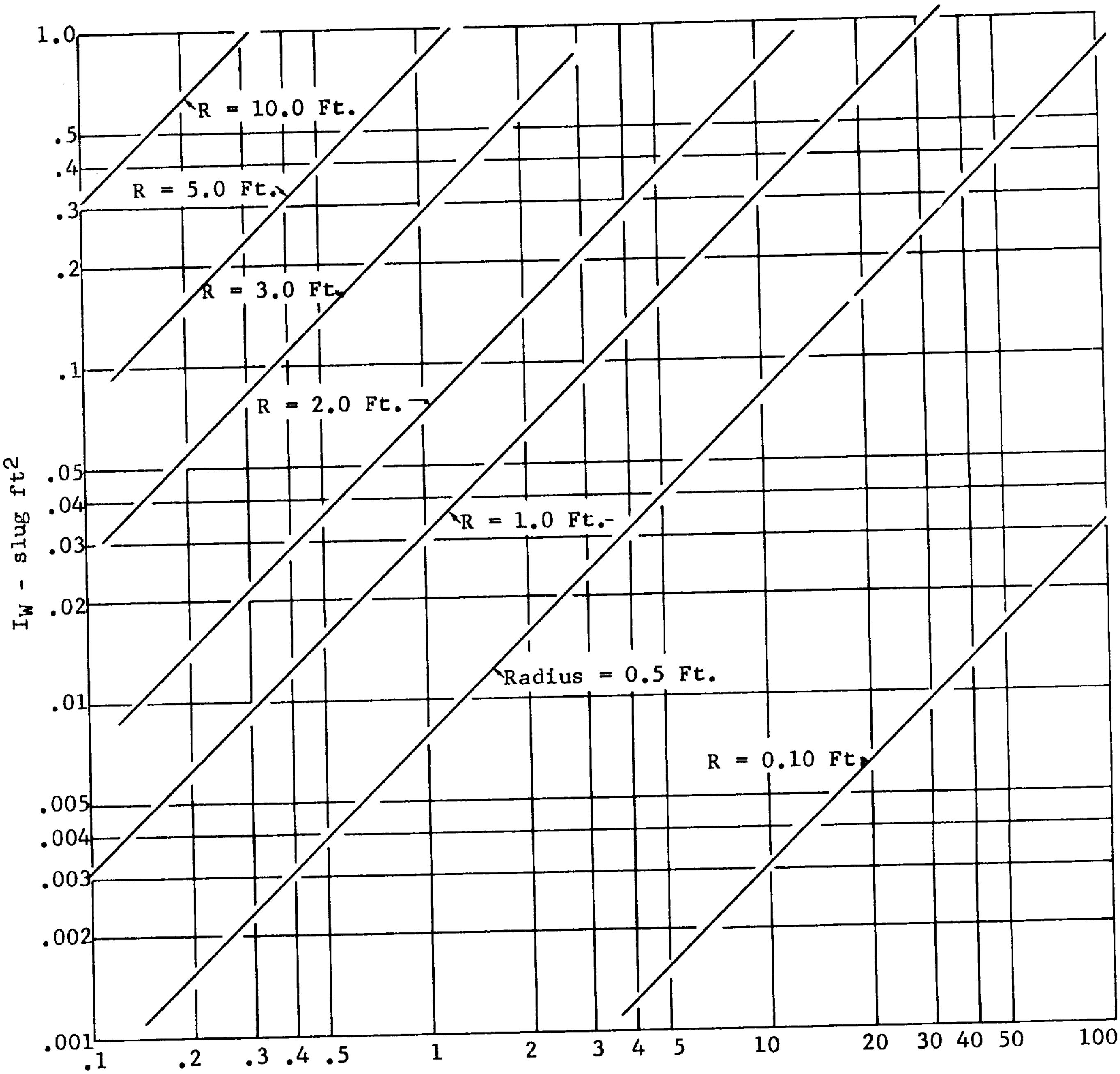


Figure J.1

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REACTION WHEEL
MOTOR DATA

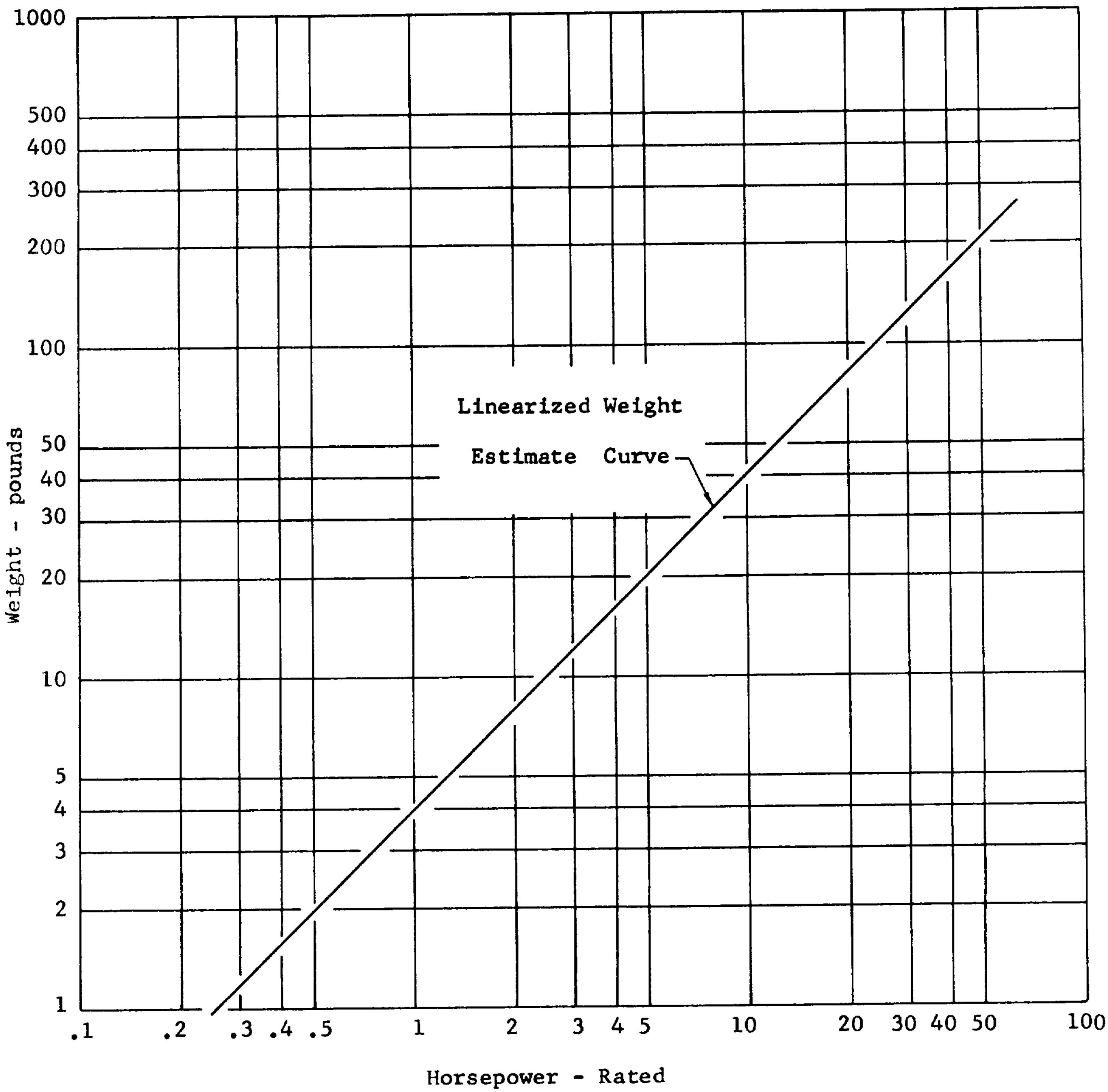

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Figure J.2

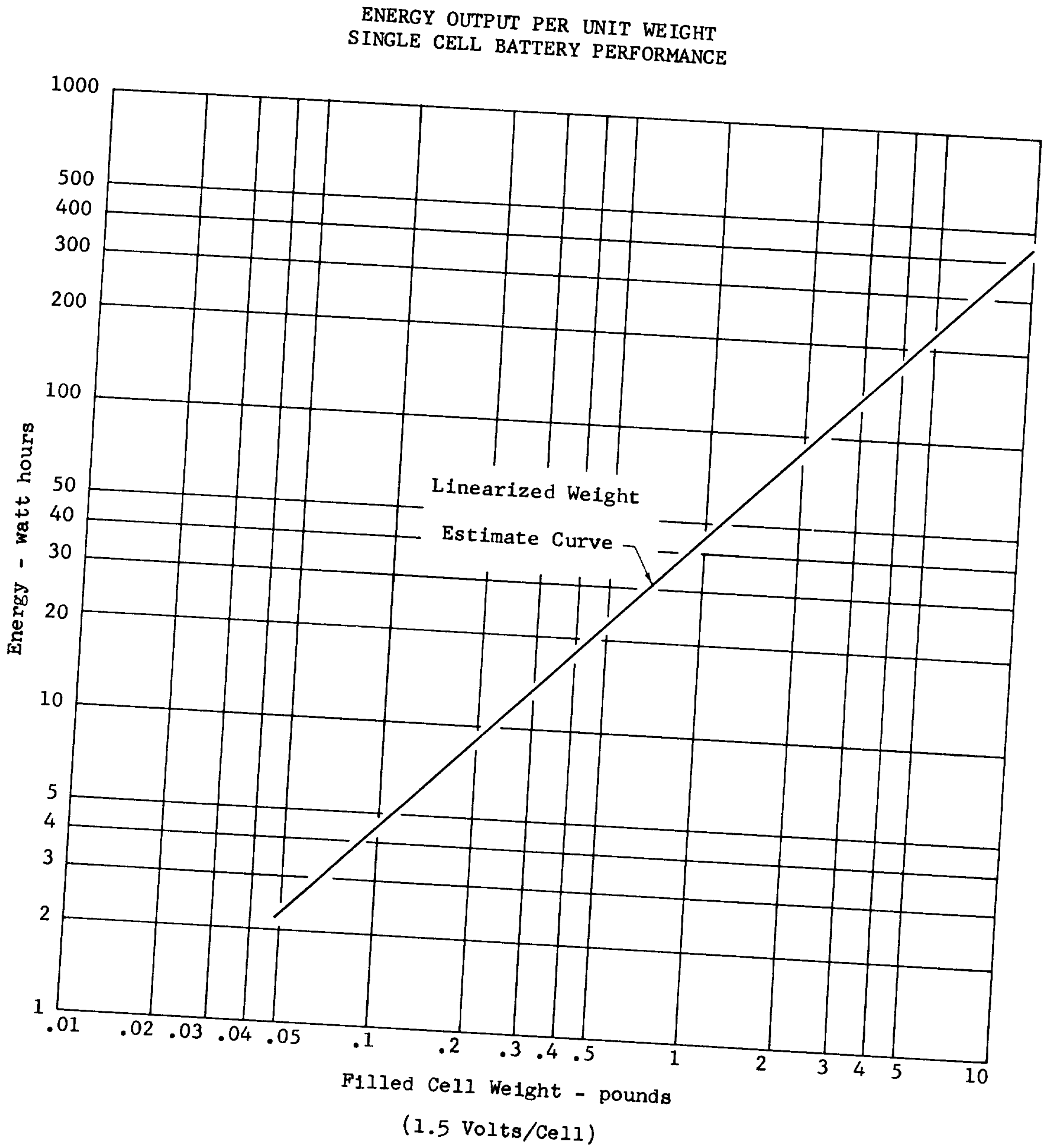

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Figure J.3

REACTION WHEEL SYSTEM WEIGHT ANALYSIS

Case 1 M = 4125 Ft.

Item	Units					
$\dot{\theta}_W$	rad/sec	0.01	0.1	1.0	10	100
I_W	slug-Ft^2	71250	7125	712.5	71.25	7.125
W_W	#	.000255	.00255	.0255	.255	2.55
r_w	Ft	94800	9480	948	94.8	9.48
Power	Ft-#/sec	41.25	412.5	4125	41250	412500
	Hr	.075	.75	7.5	75	750
	Watts	55.9	559	5590	55900	559000
Energy	Watt Hrs.					
W Pwr Sply	#	22.4	224	2240	22400	224000
W Motor	#	.3	3	30	300	3000
Σ Weight	#	22.7	227	2270	22700	227000

Case 2 M = 82.5 Ft.

Item	Units						
$\dot{\theta}_W$			0.01	0.1	1.0	10	100
I_W			82.5	8.25	.825	.0825	.00825
W_W	#	x10^{-4}	.00296	.0296	.296	2.96	29.6
r_w	Ft	x10^{+2}	948	94.8	9.48	.948	.0948
Power	Ft-#/sec		.825	8.25	82.5	825	8250
	HP		.0015	.015	.15	1.5	15
	Watts		1.126	11.26	112.6	1126	11260
Energy	Watt Hrs.		53	530	5300	53000	530,000
W Pwr Sply	#		.45	4.5	45	450	4500
W Motor	#		.006	.06	.6	6	60
Σ Weight	#		.456	4.56	45.6	456	4560

Table J.1

REACTION WHEEL SYSTEM WEIGHT ANALYSIS

$\dot{\theta}_W$	rad/sec		0.01	0.1	1.0	10	100
Case 3 M = 4125 Ft. # r_W = 1.0 Ft.							
Fixed Weight	(Motor + Power)	#	22.7	227	2270	22700	227,000
Wheel Weight	#		23×10^5	23×10^4	23×10^3	23×10^2	230
Total Weight	#		2,300,022	230,227	25,270	250,000	227,230
Case 4 M = 82.5 Ft. # r_W = 1.0 Ft.							
Fixed Weight	#		.456	4.56	45.6	456	4560
Wheel Weight	#		2650	265	26.5	2.65	.265
Total Weight	#		2650	270	72.1	459	4560
Case 5 M = 4125 Ft. # r_W = 1.0 Ft. Δt = 0.010 Sec.							
Inertia $_W$	slug-Ft^2		4125	412.5	41.25	4.125	.4125
Wheel Weight	#		140,000	14,000	1400	140	14
Fixed Weight	#		22.7	227	2270	22700	227,000
Total Weight	#		140,022	14,227	3670	22840	227,014

Table J.2

APPENDIX K

FAILURE MODE ANALYSIS

The results of a Failure Mode Analysis for a Positive Displacement Injector of the pressure actuated piston type and for solenoid valves common to a conventional bi-propellant attitude control system are contained in tables K.1 thru K.3.

POSITIVE DISPLACEMENT INJECTOR

Design Reliability Audit
Failure Mode Analysis

Part, Component, Unit, Or Subsystem	Description	Number of Parts	Description Of Assumed Failure	Item Failure Mode	Influence On System	$P\{f_i\}$ $\times 10^{-6}$	$P\{F/f_i\}$	$P\{F_i\}$ $\times 10^{-6}$	Cause or Inducer of Assumed Failure	Possible Methods To Eliminate Failure Mode
Pilot Solenoid Valve	3 Way Normally Closed	1	Valve locks open	Plunger remains extended	No impulse	11	1	11	Fatigue failure of spring, mechanical jamming.	Rigid control over design and metallurgy features. Adequate quality inspection.
			Valve locks closed	Plunger remains retracted	No impulse				Internal electrical break-down, mechanical jamming.	Rigid control over design and metallurgy features. Adequate quality insp.
										Redundancy in electric circuitry e.g. double coiling.
			Valve sticks midstroke	Plunger immovable midway, loss of GN_2	No impulse				Metal chip or foreign particle lodging improperly.	High filtration of gas-stream and material integrity.
			Imperfect seating	Loss of GN_2 response degradation.	Loss of engine efficiency				Contamination, wear, misalignment.	High filtration of gas-stream, effective material strength, design integrity.
Actuating Cylinder	Metallic Piston Elastomeric seal	1	Seizure	Plunger immovable	No impulse	.500	1	.500	Metal chip or foreign particle lodging improperly.	High filtration of gas-stream and material integrity.
			Failure of Sealing characteristics	Seepage and loss of GN_2, response degradation.	Loss of Engine Efficiency				Wear, excessive friction.	Material strength and compatibility.
Bellows		2	Rupture, pin hole leak	Propellant leakage pressure balance off.	Propellant waste	4.474	1	4.474	Defective material and weld-joint fatigue.	Heli-arc welding, multi-ply construction, generous design features, ample safety factor.
Plunger	Metallic, Rod type, rigid	2	Immovable	No propellant expulsion	No impulse	.40	1	.40	Metal chip or foreign particle lodging improperly.	High filtration to insure propellant purity, material integrity.
			Failure of Sealing Characteristics	Blow by of Propellant, change in O/F ratio, balance off	Reduction of impulse generated.				Wear, excessive friction.	Material strength and compatibility.

$P\{f_i\}$ = Probability Of Part Failure $P\{F/f_i\}$ = Probability Of Item Failure If Part Failure Occurs $P\{F_i\}$ = Probability Of Item Failure

Table K.1

POSITIVE DISPLACEMENT INJECTOR

Design Reliability Audit
Failure Mode Analysis

Part, Component, Unit, Or Subsystem	Description	Number of Parts	Description Of Assumed Failure	Item Failure Mode	Influence On System	$P\{f_i\}$ $\times 10^{-6}$	$P\{F, f_i\}$	$P\{F_i\}$ $\times 10^{-6}$	Cause or Inducer of Assumed Failure	Possible Methods To Eliminate Failure Mode
Check Valve (In)		2	Failure of Sealing Characteristics	Inefficient operation, oxidizer-fuel pressure ratio off	Reduction of impulse generated	10.0	1	10.0	Contamination, wear, misalingment.	High filtration for propellant purity, material strength, design integrity or alternative scheme.
			Spring failure	None	None					
			Valve locks closed	No propellant flow	No impulse				Metal chip or foreign particle lodging improperly. Mechanical jamming.	High filtration for propellant purity, material integrity, rigid control over design and met. features, quality inspection or alternative flow scheme.
Check Valve (Out)		2	Failure of sealing characteristics	Propellant leakage and loss, possible fuel-oxidizer mixing	Possible no thrust shut-off and propellant waste.	11.4	1	11.4	Contamination, Wear, Misalignment	High filtration for propellant purity, material strength, design integrity or alternative scheme.
			Spring failure	Propellant leakage and loss, possible fuel-oxidizer mixing	Possible no thrust shut-off and propellant waste.				Return spring fatigue failure.	Rigid control over design and metallurgy features. Adequate quality inspection.
			Valve locks closed	No propellant expulsion	No impulse				Metal chip or foreign particle lodging improperly. Mechanical jamming.	High filtration for propellant purity, material integrity, rigid control over design and metallurgical features, quality inspection or alternative flow scheme.
					TOTAL			37.774		

$P\{f_i\}$ = Probability Of Part Failure $P\{F, f_i\}$ = Probability Of Item Failure If Part Failure Occurs $P\{F_i\}$ = Probability Of Item Failure

Table K.2

CONVENTIONAL SYSTEM SOLENOID VALVES

Design Reliability Audit
Failure Mode Analysis

Part, Component, Unit, Or Subsystem	Description	Number of Parts	Description Of Assumed Failure	Item Failure Mode	Influence On System	$P\{f_i\}$ x10^{-6}	$P\{F/f_i\}$	$P\{F_i\}$ x10^{-6}	Cause or Inducer of Assumed Failure	Possible Methods To Eliminate Failure Mode
Solenoid Valve		2	Valve locks open	Loss of propellant	Propellant Waste or Full Engine Operation	22	1	22	Metal chip or foreign particle lodging improperly.	Rigid control over design and metallurgy features, adequate quality inspection.
			Valve locks closed	No propellant flow	No impulse				Internal electrical breakdown, mechanical jam.	Rigid control over design and metallurgy features, adequate quality inspection. Redundancy in electric circuitry e.g. double coiling.
			Imperfect seating	Leakage of Propellant	Propellant waste				Contamination, wear misalignment.	High filtration for propellant purity, effective material strength, design integrity.
					TOTAL			22		

$P\{f_i\}$ = Probability Of Part Failure

$P\{F, f_i\}$ = Probability Of Item Failure If Part Failure Occurs

$P\{F_i\}$ = Probability Of Item Failure

Table K.3

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